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HYDROSTATIC AND HYDRODYNAMIC ANALYSIS OF A LENGTHENED DDG-51 DESTROYER MODIFIED REPEAT

by

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June 2010

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HYDROSTATIC AND HYDRODYNAMIC ANALYSIS OF A LENGTHENED DDG-51 DESTROYER MODIFIED REPEAT

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The purpose of this thesis is to determine the feasibility of lengthening the current DDG-51 ARLEIGH BURKE class destroyers and the resulting effects on the hydrostatics and hydrodynamics. A modified repeat of a current, proven ship design would offer a more cost-effective solution for the acquisition of ships to reach the U.S. Navy goal of a 313-ship fleet in the 30-year shipbuilding plan. An analysis is performed to determine a proposed length that would be added to the ship at the parallel midbody. The current DDG-51 hullform is compared to this lengthened version, analyzing the key hydrostatic and hydrodynamic characteristics. The result is a ship that would be able to offer increased mission capability with increased weight and electrical power margins. This modified repeat would also offer potential cost savings, as compared to designing a completely new surface combatant.

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LIST OF ACRONYMS AND ABBREVIATIONS

A_M	Ship cross-sectional area
A_{WP}	Waterplane area
AAW	Anti-Air Warfare
ACTS	AEGIS Combat Training System
ADS	AEGIS Display System
AGS	Advanced Gun System
ASSET	Advanced Surface Ship Evaluation Tool
ASUW	Anti-Surface Warfare
ASW	Anti-submarine Warfare
AT/FP	anti-terrorism/force protection
B	Beam
BWL	Beam on the Water Line
BMD	Ballistic Missile Defense
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
C&D	Command and Decision
C_B	Block Coefficient
C_M	Midship Coefficient
C_P	Prismatic Coefficient
CG	Guided Missile Cruiser
CIWS	Close In Weapons System
CSG	Carrier Strike Group
DBR	Dual Band Radar
DD	Destroyer
DDG	Guided Missile Destroyer
DLS	Decoy Launching System
DSMAC	Digital Scene Matching Area Correlator
EMCON	Emission Control
ERGM	Extended Range Guided Munitions
ESG	Expeditionary Strike Group

ESSM	Evolved Sea Sparrow Missile
FCS	Fire Control System
HDTI	High Definition Thermal Imager
HO	Humanitarian Operations
INS	Inertial Navigation System
IPS	Integrated Power System
IR	Infrared
JTIDS	Joint Tactical Information Distribution System
LAMPS	Light Airborne Multi-Purpose System
LCG	Longitudinal Center of Gravity
LCS	Littoral Combat Ship
LOA	Length Over All
LPD	Landing Platform Dock
LSD	Landing Ship Dock
LWL	Length on the Water Line
NAVSEA	Naval Sea Systems Command
NSFS	Naval Surface Fire Support
ORTS	Operational Readiness Test System
PPP	Power Prediction Program
RAS	Refueling At Sea
RAST	Recovery, Assist, Securing, and Traversing
RF	Radio Frequency
SAG	Surface Action Group
SBM	Sea-based Mid-course Defense
SCFOS	Surface Combatant Family of Ships
SM	Standard Missiles
SOF	Special Operations Forces
SRBOC	Super Rapid Bloom Off-board Countermeasures
STW	Strike Warfare
SVTT	Surface Vessel Torpedo Tube
SWBS	Ship Work Breakdown Structure
T	Draft to the keel

TADIX B	Tactical Information Exchange System
TERCOM	Terrain Contour Matching
TLAM	Tomahawk Land Attack Missile
UAV	Unmanned Aerial Vehicle
UNREP	Underway Replenishment
V	Volume
VLA	Vertically Launched Anti-Submarine Rocket
VLS	Vertical Launching System
VSR	Volume Search Radar
WCS	Weapons Control System
Z_D	Stress at the deck edge
Z_K	Stress at the keel

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EXECUTIVE SUMMARY

The recent cancellation of the CG(X) program and cutbacks in the DDG-1000 and LCS programs has left the U.S. Navy struggling to find a way to affordably build the 313-ship Navy. The productions lines for the DDG-51 class destroyer are coming back online as the Navy is expecting to buy more of the reliable destroyers.

However, as the missions requirements of the destroyer grows, so must the physical size. To accommodate future systems, the destroyer needs to be lengthened. By comparing the length to beam ratios of both other U.S. Navy surface combatants and other allied warships, analysis shows that the DDG-51 could be lengthened 18 meters by utilizing a parallel midbody plug. Increasing the length by 18 meters will also increase displacement of the lengthened destroyer to roughly 11,500 ltons.

By increasing the length to beam ratio, the hydrodynamic characteristics of the ship will change. Calculations show that the lengthened DDG-51 variant will have less total resistance, which results in a 10 MW decrease in required power to reach the operational speed of 30 kts. The seakeeping of the lengthened hull also changed, with the analysis showing that the lengthened DDG-51 variant will perform better in the motions of heave and pitch, but has increased roll as compared to the baseline DDG-51 in the roll motion.

A rough order of magnitude structural analysis shows that taking the current DDG-51 structure and subjecting it to increased moments caused by the longer ship does not exceed NAVSEA limits on deck and keel stresses. By not having to significantly modify the structural design of the current DDG-51, cost savings can be realized in both the design and construction phases.

Lengthening the current DDG-51 is a viable option to meet the needs of the future Navy. Obtaining increased mission capability out of an already existing hullform, provides an affordable solution to the Navy's goal of 313 ships.

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I. INTRODUCTION

A. BACKGROUND

The backbone of the United States Navy's surface combatant force has been, and will continue to be, the DDG-51 Class destroyer. Developed during the twilight years of the Cold War, it has grown to be the largest single class of ships in the last half century. Serving in a wide variety of combat situations, the ARLEIGH BURKE destroyers have proven themselves repeatedly. This workhorse of the U.S. fleet has been the gauge that many other navies aspire towards with their own destroyers.

The DDG-51 Class destroyers were developed with a single focus, to carry the AEGIS combat system and its radar. Since the first ship was delivered in 1989, the class has undergone a major design change and multiple program extensions that allowed the fleet to expand from the original 29 hulls to an astonishing 71. This continued construction effort proves that the DDG-51 is a sound design, and one that does not have an end in the near future.

The Navy now has an interest in lengthening the destroyer to fill a capability gap in the surface combatant force. This idea was originally explored in 1989, but the research lay dormant for nearly two decades before the need for this longer version arose. Since its original design, technology has changed significantly; with newer radars and all electric propulsion emerging, the DDG-51 has been given new life.

B. PURPOSE

The purpose of this thesis is to evaluate lengthening the current DDG-51 Flight IIA destroyer with a section of parallel mid-body. Topics that will be addressed in this thesis are: basic hydrostatics and hydrodynamics, structure, and mission capabilities. Since a ship design is such a large and complex issue, a rough analysis will be explored. A detailed analysis into these topics could be useful in future studies.

C. RESEARCH TOPICS

The following question topics have been developed to focus the intent of this thesis.

1. What is the benefit of adding a section of parallel mid-body to the current DDG-51 hull form?

2. Will the increased length to beam ratio improve the power requirements of the longer destroyer hull?

3. What affect will the increased length have on the maneuverability and seakeeping of the longer destroyer hull?

4. What benefits will the increased dimensions offer to the mission effectiveness, payload flexibility, etc?

5. How will this major design change affect the cost of the DDG-51?

D. BENEFIT OF STUDY

This thesis will provide NAVSEA with another conceptual study for the continued use and improvement of the DDG-51 Class destroyer. It will also serve as another resource for the Total Ship Systems Engineering program at the Naval Postgraduate School to focus future ship design projects.

E. SCOPE AND METHODOLOGY

This thesis will provide a rough order of magnitude design study on the feasibility of inserting a parallel mid-body section into a DDG-51 destroyer hull form. A broad analysis will look at the differences between the original DDG-51 and the lengthened version concerning its mission capability, power and propulsion, hydrostatics, and hydrodynamics. From this analysis, the impact to both design and lifecycle cost will be considered. Another important factor to the design is that the technologies explored for this design need to be mature in the next five to ten years since the assumed delivery to the U.S. Navy will be 2025.

As with all ship designs, there will be a balancing act, trading one feature for another to provide a ship that will accomplish all specified missions. The driving factors in this design study will be weight and cost. Weight is important since the DDG-51 has been in service for over twenty years and with modernization and other additions, the ship class has used up its entire weight margin. Cost is another large part of this vessel's design since the recent designs and acquisitions by the U.S. Navy have been over budget.

The most important aspect of this design is understanding what the surface combatant force needs in its future ships. What mission capabilities does the current DDG-51 have that needs to continue, which are no longer necessary, and what new capabilities could be incorporated on a larger version.

Engineers at NAVSEA and private shipbuilders will be utilized to provide data and offer opinions pertaining to the direction of this research. The responses and ideas from these extremely varied resources are combined to form the final concept design. The concept hullform will be evaluated with a variety of ship design programs, including ASSET, Microsoft Excel, Rhinoceros, and a variety of ship resistance estimation codes to verify that the concept will work and attain some of the basic hydrostatic, hydrodynamic, and structural data. The hydrodynamics will also be analyzed with MATLAB codes and graphically represented.

The concept will also be continually evaluated by ship operators; the customer who someday may take this type of ship into combat. They will offer a contrasting opinion to the engineers and shipbuilders, which is a key attribute to designing a ship that can be built and serve its purpose to the fleet.

The result of this thesis will be a concept design, with a basic understanding of the ship systems and general arrangements. Recommendations and design changes from this point will allow for further research into a more specific facet of the ship or a revision to the design.

F. CHAPTER SUMMARY

This chapter provides the method by which this conceptual ship design and subsequent thesis was developed; introducing the topic, the purpose, research questions, benefit of study, and the methodology.

II. HISTORY OF THE DDG-51 DESTROYER

A. HISTORY AND FUTURE OF U.S. NAVY DESTROYERS

The foundation of the U.S. Naval surface fleet is the DDG-51 ARLEIGH BURKE class destroyer. The class was developed during the mid 1970s as a replacement for the aging Spruance class destroyers. This new destroyer would incorporate the AEGIS weapons system; carrying a variety of weapons to accomplish the three main missions; Anti-Air Warfare (AAW), Anti-Submarine Warfare (ASW), and Anti-Surface Warfare (ASUW). In 1980, the Navy initiated a design study competition between seven different shipbuilding contractors. After the initial reviews, the list was reduced to only three in 1983. On April 3, 1985, Bath Iron Works was awarded a contract to construct the first of the class and Gibbs and Cox was awarded the contract to be the lead ship design agent (Pike, 2008c).

Since the USS ARLEIGH BURKE was launched in 1989, the class has gone through one major upgrade and seen the overall production numbers exceed expectations. Multiple times in its history, the production line was shut down, only to be reopened when the Navy ordered more. The DDG-51 class was to be augmented and then replaced by the DDG-1000, the next class of destroyers. Politics and policy in the Navy has set a goal of a 313 ship Navy by 2025, where the fleet currently stands at 286 ships (Navy, 2010). This is a difficult goal to realize, requiring a dedicated effort to the construction of new ships as well as support for an aging fleet.

The DD(X) was part of an overarching concept call the Surface Combatant Family of Ships (SCFOS). The SCFOS was a plan to develop three new warships, of different sizes that would fully cover the future needs and missions of the Navy. The three ships in the family were the Littoral Combat Ship (LCS), the new destroyer DD(X), and a new cruiser CG(X). All three of these ships have experienced cost overruns and program issues, resulting in severely reduced class size or cancelation of the entire project. The destroyer and cruiser variants were to incorporate open architecture and

design features that would allow for similar systems between the two classes to keep the costs down and make maintainability and modernizations easier in the future.

Figure 1. An Artist's Concept of the SCFOS in 1997 (From Pike, 2008b)

The DD(X) program was finally developed into the DDG-1000, a stealthy advanced destroyer employing new technologies like Integrated Power System (IPS), composite superstructure, and peripheral mounted Vertical Launch System (VLS) for missiles. The original plan was to purchase seven of these new advanced destroyers, but cost overruns and a change in Navy policy led to the class being reduced to only three ships. In a Congressional review of the DDG-1000 program, documentation showed that between FY1995 and FY2009 $15.3 billion in funding has gone to this program; including about $7.3 billion in research and development funding and $8.0 billion in ship procurement (O'Rourke, 2009). Though this class will offer a technology test platform for all future vessels, it will not fill the role of the main U.S. Navy surface combatant. A DDG-1000 artist rendition is shown in Figure 2.

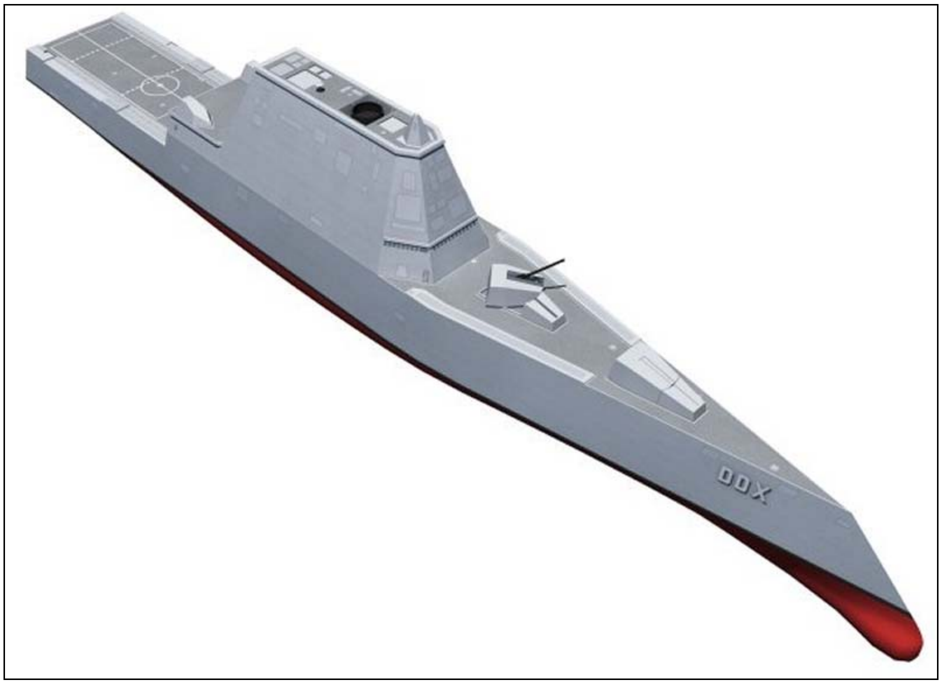

Figure 2. Artist’s Concept of the DDX, Which Would Later Become DDG-21 (From Pike, 2008b)

The DDG-1000 program is not the only acquisition program plagued with cost overruns and budget cuts. LCS experienced massive cost problems during the design and construction of the first two ships, a Lockheed-Martin/Northrop-Grumman team and an Austal-General Dynamics team building two separate designs. The initial contract was a ship that cost $460 million, but the costs spiraled until the ships cost $637 and $704 respectively (Cavas, 2009). This has led to the cancelation of the third and fourth ships until deals can be worked out with the shipbuilders on how to lower costs.

Another program that experienced cost issues was the CG(X) program. The SCFOS concept planned that the CG(X) would use either the same hull form as the DD(X) or a scalable version. This large-multirole cruiser was to accomplish all of the missions of the DD(X), as well as theater Ballistic Missile Defense (BMD), which will be discussed in greater detail later. This program ran into many technical and financial hurdles during the concept stage of the process, and funding was cut.

As seen by these examples, cost is the most important factor in the design of a new ship, the key to the future U.S. Navy fleet is its affordability. The reason that the production line has been restarted on the DDG-51 is that it is an affordable solution to enlarging the fleet. The rest of this chapter will describe the different flights of the DDG-51 that were produced as well as the concept of a lengthened destroyer that was considered in the late 1980s.

B. DDG-51 FLIGHT I

The initial ARLEIGH BURKE-class guided missile destroyer is 506 feet long and has a 62-foot beam. They are powered by four General Electric LM2500 gas turbine engines, turning two shafts with controllable pitch propellers; giving them a maximum speed in excess of 30 knots and a cruise speed of 20 knots. At the cruise speed, the destroyer has a range of 4,400 nautical miles. Power generation is derived from three Allison 501 gas turbine generators, making three megawatts each.

The driving force behind the DDG-51 class destroyer is the AEGIS weapons control system, which is driven by an advanced, automatic detect and track, multifunctional phased-array radar, the AN/SPY-1. This ship is designed around this system, due to the large size and weight of the radar arrays. The AEGIS combat system and its accompanying weapons will be described in more detail later in this report.

ARLEIGH BURKE destroyers have many distinct design features, starting from the bow; the first weapon is the five-inch 54-caliber gun, used for the fire support and anti surface warfare missions. Just aft of the gun is the forward MK 41 Vertical Launch System (VLS), 32 tubes that can carry a variety of missiles (they will be discussed in the chapter III). At the front of the forward superstructure is a MK 15 Close-In-Weapons System (CIWS), offering the ship its close in air and surface defense. The forward superstructure houses all four of the SPY-1 radar arrays, as well as the bridge, other radar arrays, the mast, countermeasures, and the intakes/exhaust for the forward engine room. The mast itself is one of the defining features of the DDG-51 class of destroyers, being raked back for an aesthetically sleeker appearance.

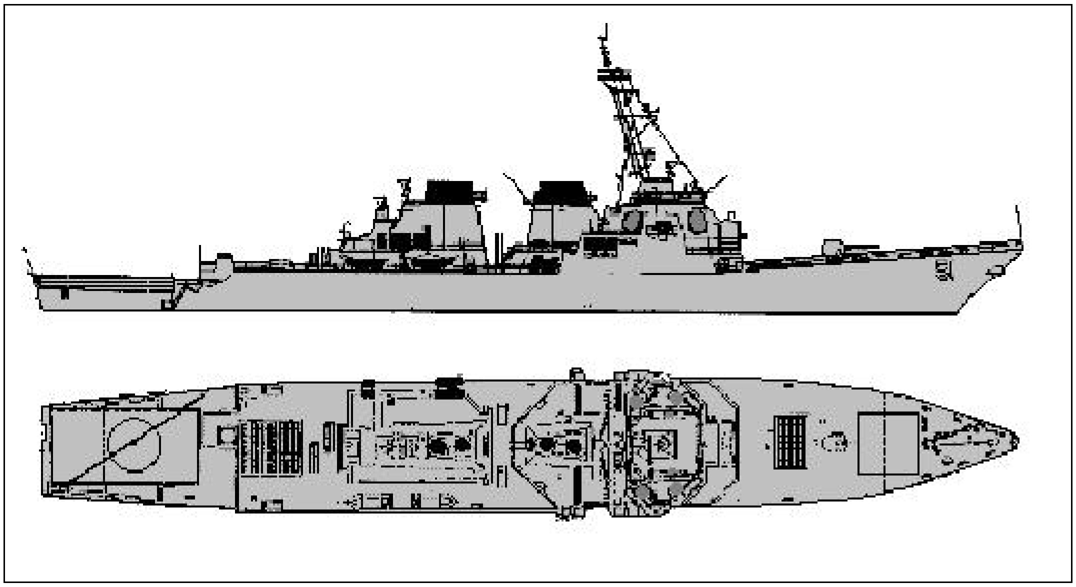

Figure 3. Schematic of a DDG-51 Flight I (From Pike, 2007b)

The area between the forward and aft superstructures holds the stations for Underway Replenishment (UNREP), the Refueling At Sea (RAS) connections, and the ships two small boats. Housed on the aft superstructure are the intakes/exhaust for the aft gas turbines, two radar illuminators, and the aft CIWS mount. Further aft is a 64 cell VLS and then the helicopter landing pad. This rear helicopter landing pad can support helicopters for other vessels but had no hangars or means to embark a helicopter. The DDG-51 carried a compliment of 300 sailor and 23 officers. Figure 4 is a drawing of the DDG-51 Flight I.

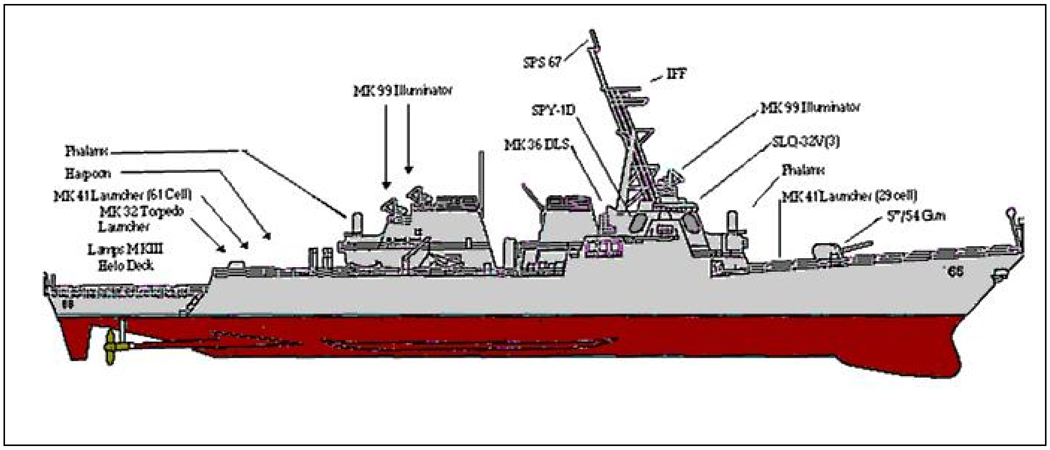

Figure 4. Schematic Drawing With System Labels of the DDG-51 Flight I (From Pike, 2007b)

C. DDG-51 FLIGHT II AND IIA

The Flight II upgrade only affected hull numbers 72–78. Since AEGIS played such a vital role in the development of this destroyer, the largest upgrade to the Flight II ships was the new baseline 6 version of AEGIS. This incorporated the ability to launch a modified version of the Standard Missile 2. Other improvements included the Joint Tactical Information Distribution System (JTIDS) Command and Control Processor, Combat Direction Finding, the Tactical Information Exchange System (TADIX B), and SLQ-32(V)3, an update to the self defense radar. There were no physical changes to the hull, crew size, or capability of the DDG-51 for these seven vessels.

The most significant change to this ship class came with the construction of the Flight IIA variant. The largest of the changes was lengthening the ship initially by five feet, but later nine feet overall to extend the length of the helicopter pad and incorporate two helicopter hangars into the rear superstructure. These organic SH-60R helicopters would utilize the Light Airborne Multi-Purpose System (LAMPS MK III) to greatly add to the DDG-51 class's ASW capability. The helicopter capability also requires the install of the Recovery, Assist, Securing, and Traversing (RAST) system to assist in the

handling of the helicopters. The addition of the helicopters also requires an increase in the crew size, now holding 348 crew and 32 officers.

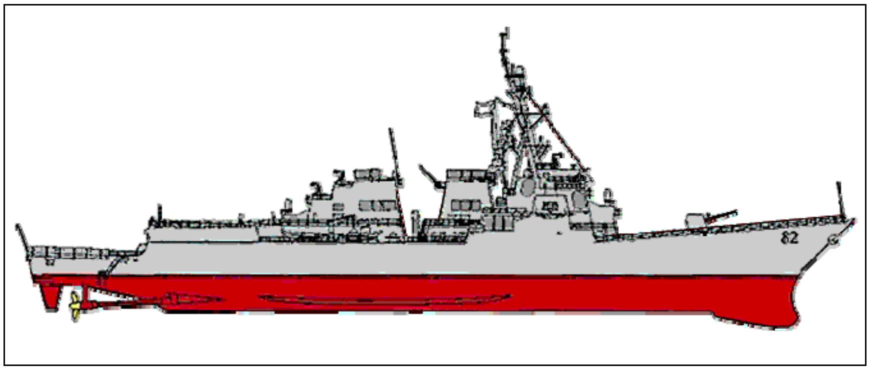

Figure 5. Schematic Drawing of the DDG-51 Flight IIA (From Pike, 2007b)

Along with the helicopter hangars, the rear superstructure changed the location of the VLS modules, raising them and running them between the two hangar bays. The crane system was also removed from the forward and aft VLS modules, allowing six more missiles to be carried. Because of the increased size of the aft superstructure due to the hangars and raised VLS modules, the aft facing SPY 1D on the forward superstructure had to be raised 8 feet, to prevent a radar shadow.

Another large modification to the Flight IIA was an upgrade to the AEGIS system, the baseline 6.1. The last series of ships, DDGs 91–112, will have the baseline 7 install, where the entire AEGIS system will have commercial computing hardware.

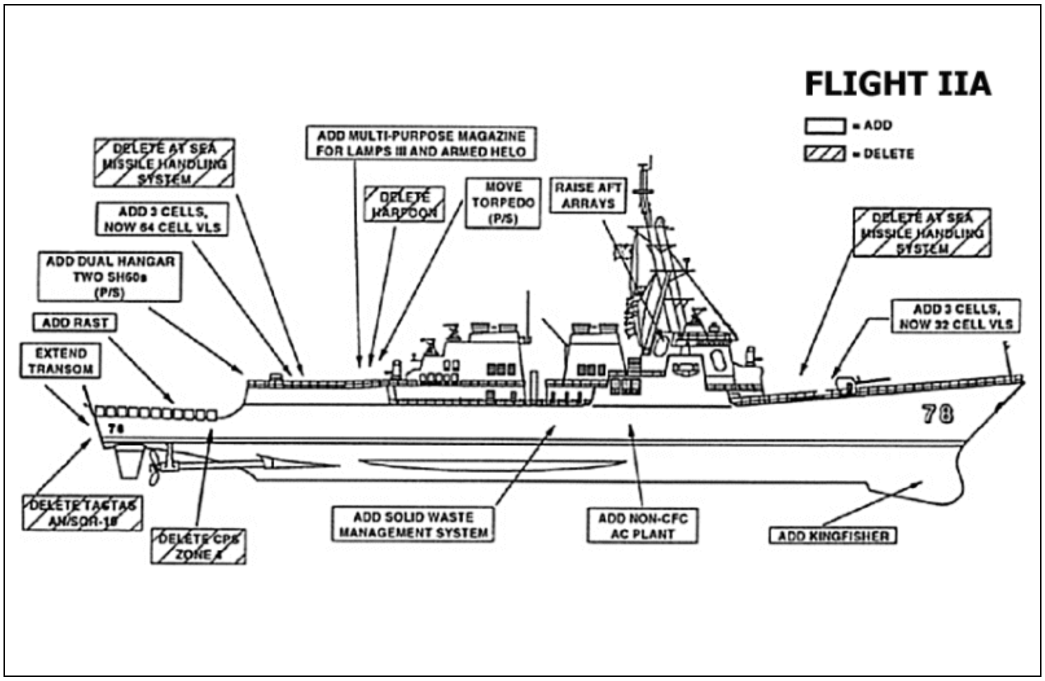

Figure 6. Schematic Drawing With System Labels of the DDG-51 Flight IIA, Showing What was Added or Removed Since the Flight I Vessels (From Pike, 2007b)

Other changes to the hull and mechanical systems were not visually apparent. Due to the increased center of gravity, lighter superstructure scantlings were utilized and thicker hull plates were used on roughly 75 percent of the length. The propellers and rudders were modified to reduce the amount of cavitation. The high-pressure air system was removed and bled air from the gas turbine generators was used to start the main propulsion gas turbines. The stern was also fit with a combination wedge/flap that improved the fuel efficiency at cruising speeds.

D. DDG-51 FLIGHT III CONCEPT

In April of 1988, NAVSEA was tasked with evaluating the feasibility of significant upgrades to the DDG-51 class of destroyer. Since the first hull had not even been delivered to the Navy at that point in time, this was a purely conceptual study. There were four cornerstone enhancements that were important to incorporate in this design study; helicopter hangars, 32 additional VLS cells, combat system upgrades, and

the ability to support a warfare commander. At this point, the Flight IIA was not yet finalized; the goal of helicopter hangars was still a novel idea for this class.

For this study, many of the ship systems remained the same, with the largest physical difference being an increase in length of 40 feet. The location of this lengthening and its resulting impact to the four cornerstone enhancements was studied through the evaluation of 10 different concepts.

The report was published in May of 1989, and it contained many of the changes that would later become the DDG-51 Flight IIA. This report made clear that a lengthened DDG-51 was feasible and would offer greater capability to carry out many of its missions. Table 1 compares some of the key parameters and characteristics of the as-built Flight I and IIA ships and the conceptual Flight III.

Table 1. Comparison Between the DDG-51 Flight I, Flight IIA and Conceptual Flight III

Characteristic	Flight I	Flight IIA	Flight III(concept)
LOA ft (m)	505 (153.9)	513 (156.4)	550 (167.6)
LWL ft (m)	466 (142)	466 (142)	512 (156.1)
Beam, max ft (m)	66 (20.1)	66 (20.1)	66 (20.1)
Beam, WL ft (m)	59 (18)	59 (18)	60 (18.3)
Draft ft (m)	31 (9.4)	31 (9.4)	41 (12.5)
Crew	300	348	355
Officers	23	32	38
LM2500	4	4	4
AL501	3	3	4
Displacement, Lightship lton	8300	9217	11896
Displacement, Full lton	7063		8957

This concept study and its results were used as a reference for this thesis as the design of a lengthened destroyer matured. Though the propulsion/electric plant, weapons, sensors, and general arrangements were different, it still offered a comparison for the key factors such as metacentric height, required propulsive power, and displacement.

E. MISSIONS

The point of a warship is to be able to go to sea, protect the sea lanes of communication, and take the fight to the enemy's shores instead of our own. It should be able to be forward deployed and accomplish wartime operations within a hostile battle space with the ability to coordinate with joint and/or allied sea and aviation forces. It should operate offensively in a high density, multi-threat environment independently or as an integral member of a Carrier Strike Group (CSG), Expeditionary Strike Group (ESG), or Surface Action Group (SAG). The capabilities of the modified DDG-51 will be divided into three main areas: core functions, primary missions, and secondary missions.

1. Core Functions

Core functions represent what any ship needs to be able to accomplish when acting as a surface combatant. These include: mobility; navigation; Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance (C4ISR); self-defense; Anti-Terrorism/Force Protection (AT/FP); and emission control (EMCON). Any warship needs to be able to accomplish these functions before it can carry out its primary and secondary missions.

2. Primary Missions

These missions are what vary from warship to warship; a carrier's mission is to launch aircraft, an LSD or LPD mission is to carry Marines to the shore; and the mission of a surface combatant, such as the modified DDG-51, is to be 'the tip of the spear.' The four primary missions that this lengthened destroyer must be able to accomplish are ASW, ASUW, AAW, and strike warfare (STW).

Anti-submarine warfare is the detection, identification, tracking, and capability to destroy a submarine. This requires sonar and other underwater sensors that can positively identify a submarine as an enemy's and not one of our own. Also the destroyer must have the weapons capable of destroying the submarine, usually in the form of torpedoes.

Anti-surface warfare is the ability to identify and destroy other enemy surface combatant vessels. Radar and other sensors are used to locate and identify these other ships, usually well over the horizon. The targets can be attacked with a wide variety of weapons; normally missiles and the deck guns.

Air warfare is the ability of the destroyer to both attack an airborne threat offensively and defend against an attack. Modern warships usually have a layered defense against aircraft and anti-ship missiles that consists of missiles, large caliber guns, small caliber guns, and countermeasures.

Strike warfare is the ship's ability to take the battle to the enemy ashore. This is in the form of land attack missiles and large caliber guns. The use of the deck gun in support of ground troops ashore is referred to as Naval Surface Fire Support (NSFS) and still falls under the Strike Warfare mission.

3. Secondary Missions

The secondary missions of the destroyer both support the core functions and primary missions; and offer a wealth of mission opportunities that make this vessel a truly multi-mission platform. The true ability of a refined destroyer is that the crew is able to adapt the vessel to accomplish any mission that presents itself. A list of these secondary missions is below:

- Humanitarian Operations (HO)
- Sea Presence (Deterrence)
- Anti-piracy
- Special Operations Forces (SOF) Support Missions
- CSG/ESG Support
- Full-spectrum littoral dominance (Enter defended littoral waters and conduct sustained operations there)

- Aviation Capabilities
- Small-boat Capabilities
- Radars
- C4I/networking capabilities
- Battle Force Defense capability (net-centric warfare)
- Counter-fire detection capability
- Littoral (near-land radar clutter)
- Mine detection and avoidance (mines in shallow-water regions)
- Deploy Countermeasures (for missiles or torpedoes) (flares, chaff, decoys, etc.)
- Launch and recover Unmanned Aerial Vehicles (UAVs)
- Embark, operate, and maintain helicopters
- Embark small boats (deployed and recovered)
- Underway replenishment (fuel, stores, ammunition, and equipment)

4. Ballistic Missile Defense

The Ballistic Missile Defense (BMD) mission is at the forefront of the Navy's future. The current DDG-51 class destroyers and CG-47 class cruisers can be modified to carry out this mission, but it is not a fully integrated system yet. In both the DDG-1000 and CG(X) designs, this mission was considered a top priority and the vessel was developed into the fundamental design to accomplish this mission. However, the future of the ballistic missile defense system is difficult to predict.

The current weapon used for BMD is the Standard Missile 3 (SM-3), which has been successful both in test firings and in the shooting down of an errant satellite in early 2008. This is currently launched from the MK-41 VLS. This system has been a very reliable launching system, but has been determined to be too small for future missiles. The future missile is currently planned to be the SM-6, which requires a larger launcher. DDG-1000 developed a periphery vertical launch system, where the missiles are along the deck edge instead of a large module in the middle of the ship. Though the periphery

launch system was not found to be as effective as the Navy had hoped, the technology of this MK-57 can be adapted to a standard VLS module that can be placed on centerline.

The other technological hurdle that the lengthened DDG-51 will have to negotiate is the radar system. Currently the SPY-1D radar and the AEGIS fire control system can be modified to accomplish BMD but not as its primary mission. Though the topic is currently classified, and therefore will not be explored in this thesis, the new radars will require more power, more cooling capacity, and more volume and weight within the ship. These will be discussed and accounted for in later chapters.

Ballistic Missile Defense must become a primary mission of the lengthened DDG-51, and the systems to support the mission must be incorporated into the design. The only way to prepare the ship for these future modifications is to build enough of a weight margin into the ship to allow for the additions.

F. CHAPTER SUMMARY

In this chapter, the history of the DDG-51 is explored, showing the design changes between the two constructed Flights and the conceptual design of the DDG-51 Flight III. To better understand the requirements that may be placed on a lengthened DDG-51 variant, the missions of a typical destroyer are reviewed, including Ballistic Missile Defense.

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III. COMBAT SYSTEMS

The ARLEIGH BURKE destroyers are considered ‘the tip of the spear,’ and as the largest class of modern destroyers, their weapons have to be the best. The modern surface combatant must be able to accomplish a wide range of missions and these various missions require specific sensors and weapons.

The lengthened variant will use many of these same weapon and sensor systems from the DDG-51 destroyer for two main reasons; cost and compatibility. By using many of the already available and battle-tested systems as the current vessels, the cost and risk of the program drop significantly. Also, by utilizing current systems, less time and money will be spent training crews and parts for these systems will be more widespread throughout the fleet.

Using current systems can also bring about a lack of new technology. The lengthened DDG-51 needs to incorporate future modernization into the design, both in hardware and software. For a vessel that may be in the fleet upwards of 40 years, the capability for the ship to be easily modernized will be vital; allowing it to be fully capable for its entire life.

The legacy systems, ones that are currently on the ARLEIGH BURKE Flight IIA ships, will be briefly discussed, followed by the presentation of newer weapon systems that could be installed on this lengthened variant of the DDG-51 destroyer. Many of these new systems, due to their physical characteristics could require significant changes to the arrangement of the ship. Changes like these could be introduced later in the ship’s life as flight upgrades.

A. LEGACY SYSTEMS

These legacy systems, all currently on the DDG-51 Flight IIA’s, are all capable systems, but they too will undergo large modernizations over the system life. These legacy systems could also become antiquated and be fully replaced during the life of the ship. These legacy systems represent the sensors, weapons, and countermeasures.

1. Sensors

a. AN/SLQ-32(V)

The AN/SLQ-32 is a surface ship radar detection, jamming and analysis system. The system has been upgraded several times over its history to include improved electronic countermeasures and radar jammers. It has full-threat band frequency coverage, 360-degree instantaneous azimuth coverage, 100 percent probability of intercept, simultaneous response to multiple threats, and is cost effective to implement and support. Using the AN/SLQ-32(V) Electronic Warfare Improvement Program and Engineering Change Proposals; the system is strongly supported for the future (Jane's Radar and Electronic Warfare Systems [REWS], 2009b; Raytheon, 2005; Reinking, 2009).

Figure 7. Picture of a SLQ-32(V) Mounted Shipboard (From Defense Industry Daily, 2009a)

b. AN/UPX-29(V) Interrogator System

The Identification of Friend or Foe (IFF) system utilizes a challenge and reply technique to distinguish contacts in a multi-target environment. It is the primary positive means of aircraft identification in air defense operations. Targets can be

classified at friendly, hostile, or neutral. The IFF system uses an independent radar antenna and can be electronically steered to query pop-up targets and can provide interrogation on a target within 25 microseconds. This system is old, but reliable. Some upgrades are in progress, such as replacement with a digital transponder (Pike, 2005a; Pike, 2005c).

c. AN/SPS-64(V) Navigation and Search Radar

The AN/SPS-64 is a surface search and navigation radar. It operates in the I/J bands or E/F bands and is compatible with the 25, 50, or 60 kW transmitter and display indicators. In the display, the system provides a combination of radar information, collision avoidance, and navigation data. The modular design of this system allows for over 15 different radar configurations where there can be an intermixing of displays and transceivers (Jane's REWS, 2009d).

Table 2. AN/SPS-64(V) Radar Data

	I/J Band	E/F Band
Frequency Range	9,375 ± 25 MHz	3,030 ± 25 MHz
Peak Power	10, 25 and 50 kW	60 kW
Wavelength	3 cm	10 cm
Range	18.3m – 118.5 km	27.4 m– 1,118.5 km

Figure 8. AN/SPS-64(V) Radar (From Wikimedia, n.d.)

d. AN/SPS-67(V) Search Radar

As a surface search radar, the AN/SPS-67 operates in the G band (5.4–5.8 GHz). The system consists of a transceiver, video processor, radar control unit, and antenna controller with safety switch. All of these are housed in self-contained cabinets that make installation easy. Upgrades have included narrowing the pulse mode for better navigation and small target resolution, and adding a digital video clutter suppressor and interference suppressor. There is also a standard electronic module technology and built-in test systems that have improved performance as well. The currently installed variants on the ARLEIGH BURKE class include gunfire support capability, digital moving target indication, automatic target detection, track-while-scan for surface targets, gun target designation and AEGIS Command and Decision (C&D) interfaces (Jane’s C4I Systems, 2009; Jane’s REWS, 2009c).

Table 3. AN/SPS-67 Radar Data

	G Band
Frequency Range	5.4-5.8 GHz
Peak Power	280 kW
Wavelength	5.5 cm
Range	104 km

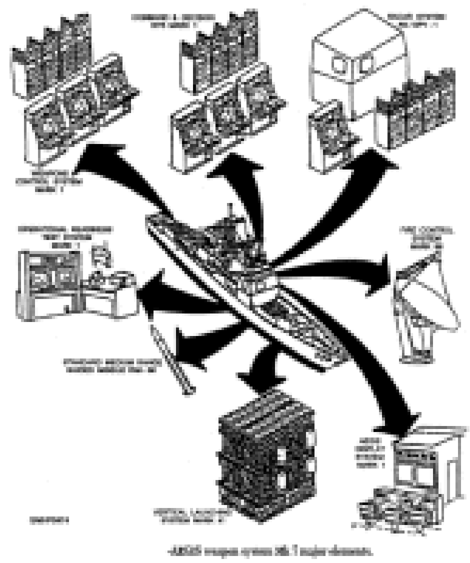
Figure 9. AN/SPS-67 Display (From Pike, 2005c)

e. AEGIS Weapon System Mk 7

The AEGIS weapon system is an advanced, automated detect and track, multifunctional phases array radar that is able to perform search, track and missile guidance functions simultaneously with over 100 targets. The core of the system is the computer based C&D element and it allows operations against air, surface and subsurface threats. The AEGIS system has nine parts: SPY radar, C&D, Weapons Control System (WCS), Fire Control System (FCS), VLS, Standard Missiles (SM), AEGIS Display System (ADS), Operational Readiness Test System (ORTS) and the AEGIS Combat Training System (ACTS) (Jane's C4I Systems, 2005; Pike, 2008e).

The C&D system is a computer and display system that coordinates and controls the AEGIS system though a manned interface stations. It automatically manages and interfaces with air, surface and sub-surface engagements, electronic warfare, data links, IFF challenges and the WCS. The C&D system is the means by which most of the combat suite communicates with each other. Any newly installed systems would be managed by this program (Pike, 2008e).

The FCS is connected to the C&D system through the WCS. The FCS controls the loading and arming of the selected weapon, launches the weapon. Additionally, FCS controls the three illuminators that provide terminal guidance for Ship Launched SM-2 Anti-Air Missiles. The illuminating radar in conjunction with the SPY 1-D radar produces the very narrow beam of Radiofrequency (RF) energy that is needed to determine, with accuracy, whether there is one target or multiple targets (Pike, 2008e; Pike, 2008f; Pike, 2008g).



AEGIS Architecture Diagram (From Pike, 2008e)

f. AN/SQS-53 Sonar System

The sonar system is a hull-mounted passive and active high power sonar system (190 kW). It utilizes three active modes: surface duct, bottom bounce, and convergence zone. The system is 1.6 m high by 4.8 m diameter cylindrical array of transducer elements housed in a bulbous dome on the bow of the ship, below the waterline. The sonar system operates from 3-192 kHz and is part of the overall USW combat system that includes the Kingfisher capability (small object avoidance), the SQQ-89 (Mk 116) fire control system, torpedo tubes, and NIXIE (Jane's UWS, 2009b; Jane's UWS 2009c).

Figure 10. AN/SQS-53 Sonar System (From Gross, 2009)

2. Countermeasures

a. Nulka Active Missile Decoy System

Nulka is an active missile decoy, operating in the I and J bands, that can be used in all weather for self-protection of vessels against anti-ship missiles. The decoy detects and amplifies all in-band signals and thus can engage multiple attacks. The system can be used in automation or manual mode and over the course of its history, has been funded through several companies and in joint work with Australia. The self-contained FCS of the Nulka decoy allows this system to be installed on vessels that would not normally have the capabilities to fire such a system. This characteristic is another reason why this is proven technology (Jane's REWS, 2009a).

Figure 11. Nulka Launcher Deploying Decoy (From U.S. Navy, n.d.)

b. Super Rapid Bloom Offboard Countermeasures (SRBOC) Decoy Launching System (DLS)

The SRBOC is a deck mounted chaff and Infrared (IR) decoy flare launching system that uses mortar-type munitions. The system is comprised of two units containing six launch tubes each that are positioned at different angles to ensure best coverage. By having multiple sites that can control the launch from makes this system worth maintaining. It also has a possible future upgrade to an automated launch of expendable munitions where the threat, wind speed and navigation data can be incorporated to get an optimized countermeasure response (Jane's REWS, 2009e).

Figure 12. SRBOC Launcher (From Just the Facts, 2009)

c. AN/SLQ-25A NIXIE

The final piece of the sonar system, AN/SLQ-25A NIXIE is a surface ship torpedo defense system that is streamed out behind the vessel during a USW situation (Jane's UWS, 2009c). It emanates an acoustic signature that mimics the ship and provides a target for an incoming torpedo.

d. AN/SQQ-28 Light Airborne Multi-Purpose System (LAMPS)

The LAMPS system is sonar processing system that utilizes sonobuoys and a dipping sonar transponder from a SH-60 Seahawk helicopter to provide an accurate detection and targeting of underwater threats. The SH-60 helicopters greatly increase the area of coverage in the ASW mission and have the ability to immediately pursue a hostile target with an Mk-46 or 50 torpedo (Pike, 2005d).

Figure 13. An SH-60B Seahawk Helicopter Fitting with a LAMPS MK III Dipping Sonar (From Pike, 2005d)

3. Weapons

a. Vertically Launched System (VLS) MK-41

The MK-41 VLS is a vertical missile launching system that can launch a variety of different missiles that are packaged separately into an individual canister. The VLS system includes the physical structure, armored hatch covers, a gas-management system, and accompanying electronics. Each cell has its own electronics and

programmable power supply, each with two supply functions for flexibility in varying the voltage to match the chosen missile. A standard canister is 7.2 m long, 7.1 m wide, and can weigh up to 4,091 kg and fits into a VLS cell. Current missiles carried in the VLS are Standard Missiles (SM), Evolved Sea Sparrow Missiles (ESSM), Tomahawks, and Vertically Launched Anti-Submarine Rockets (VLA) (Jane’s Naval Weapon Systems (NWS), 2009a).

Figure 14. VLS Launches (From MotivatedPhotes.com, n.d.)

b. RIM-162 Evolved Sea Sparrow Missile (ESSM)

An ESSM is a short range, ship based, theater defense missile. It is 3.84 m long with a diameter of 0.254 m and weighs 295 kg at launch. Four ESSMs are packed into one VLS canister with a full canister weight of 2,590 kg. An ESSM has a range of 45 km, and includes a dual-mode IR and semi-active radar seeker with a tail control assembly (Jane’s Strategic Weapon Systems, 2008).

Figure 15. ESSM Launch (From Morton, 2009)

c. Standard Missile (SM)

The SM-2 and SM-3 variants are compatible with VLS. The SM-2's mission of AAW and area defense, can achieve speeds of over Mach 3, has a weight of up to1497 kg, and a range of up to 130 nautical miles. The SM-3 is a Sea-based Mid-course Defense (SBM) for ballistic missile defense, can achieve Mach 3, weighs 1,500-2,086 kg, and has a range of 650 nm (Jane's NWS, 2009f).

Table 4. Standard Missile Data

	SM-2MR	SM-2/IIIA/B	SM-2/IVA	SM-3
Weight (kg)	708	708	1,497	1501/2086
Speed (Mach)	M2.5	M3+	M3	M3
Range (nm)	90	90	130	650
Altitude (m)	19,800	20,000	33,000	Not known

Figure 16. Standard Missile Launch from a VLS (From Defense Industry Daily, 2009c)

d. RUM-139A Vertically Launched Anti-Submarine Rocket (VLA)

A VLA is a Mk 46 torpedo that uses a rocket booster to initially provide the torpedo with a high speed aerial delivery. The dome-shaped, plastic nose cap is design protect the sonar transducer during the high-speed water entry, but break apart upon activating a water/pressure sensor. This use of a torpedo allows a standoff safety range not only from the torpedo itself, but also from the target. More recent versions can use the Mk 54 torpedo as well. The system utilizes an active/passive acoustic homing head and is powered by liquid mono-propellant motor (Jane's NWS, 2009a).

Table 5. Weapon Data for a VLA

	VLA
Length (m)	4.89
Diameter (cm)	35.81
Weight (kg)	640
Range (nm)	9

Figure 17. VLA Launch (From Pike, 2006)

e. MK-32 Surface Vessel Torpedo Tubes (SVTT)

The SVTT is a set of triple torpedo tubes that launch either the MK-46 or MK-50 torpedoes. There is a launcher on each side of the DDG-51, along with more torpedoes stored in a magazine. The torpedoes are launched using the MK 116 fire control system. The MK 116 provides tactical data processing, contact management, target engagement processing and weapons' control (Jane's NWS, 2009c; Jane's NWS 2009h).

Figure 18. MK-32 SVTT (From Wikipedia, 1988)

f. MK-15 Close In Weapons System (CIWS)

The MK 15 CIWS is a weapon system designed to provide close to the vessel defense against anti-ship missiles or inbound small boats through tracking both the target and the rounds fired. The CIWS system consists of local and remote control panels, electronics cabinet, mount and train drive assemblies; in addition to the 20mm gun assembly with accompanying fire-control radar and servo assembly. The Baseline 1 group has a 3.1 m length, 5 m height and weights 6.17 tons. The system uses 31.75 kg of seawater per minute for cooling. In the extreme, the CIWS can operate for 30 minutes before shutting down, when cooling is not available. The CIWS magazine takes up to 30 minutes to reload, and with the upgrade of the High Definition Thermal Imager (HDTI) can detect targets out to 4.5 nm, and begins firing at 1 nm with a maximum probable kill at 460 m. The system can react in 3 seconds, has a muzzle velocity of 1,030 m/s, fires 4,500 rounds per minute and is powered with 440 V, 60 Hz, 3-phase electricity and requires 18kW when searching and 70 kW of power when firing (Jane’s NWS, 2009e). Even though this system is old, it is well established and has been proven effective.

Figure 19. Close In Weapons System (CIWS) (From Defense Industry Daily, 2009b)

g. MK-45 5 Inch Deck Gun

The five-inch gun is a medium caliber dual purpose gun, providing NSFS and ship-to-ship defense. The previous design was for the 54-caliber system; however the newest upgraded system is that of the 62 caliber. The gun fires 16–20 rounds per minute when firing conventional rounds and five to 10 rounds per minute when firing Extended Range Guided Munitions (ERGM). Exit velocity of the barrel is approximately 800 m/s with a max altitude of 15,000 m. The five-inch, 62-caliber gun can fire conventional, Improved Conventional Munitions (ICM), and ERGM (Federation of American Scientists (FAS), 1998; Jane's Ammunition Handbook, 2009; Jane's NWS, 2009d).

Table 6. Five Inch Ammunition Ranges

	Conventional	ICM	ERGM
Range (nm)	12.4	20	63

Figure 20. Five Inch Gun (From Matthews, 2008)

h. Tomahawk Missile

A Tomahawk is a land attack cruise missile capable of loitering and in-flight retargeting while conducting battle damage assessment. The Tomahawk Land Attack Missile (TLAM) has Terrain Contour Matching (TERCOM), Inertial Navigation System (INS), and Digital Scene Matching Area Correlator (DSMAC) (Jane's NWS, 2009b).

Table 7. Tomahawk Data

	Tomahawk (All Variants)
Length (m)	6.25
Diameter (m)	0.52
Weight (kg)	1587
Speed (Mach)	M0.72
Range (nm)	1000+

Figure 21. Tomahawk Missile Launch (From MilitaryPictures.info, 2006)

B. NEW SYSTEMS

This lengthened variant of the DDG-51 is in a tough position where it will have to be a balance of new, high-risk systems and the retention of legacy systems to keep the cost of redesign to a minimum. But this lengthened hull form does offer an opportunity to incorporate systems that are not even able to be backfit onto the DDG-51 Flight IIA due to weight and balance restrictions.

Three of these new systems directly support the BMD mission; the radar, the missile, and the missile launcher. As previously discussed, the BMD mission set is one of the top priorities for the U.S. Navy. Many of the current DDG-51 Flights IIA are being modified to accomplish this mission using an AEGIS BMD upgrade. The there are currently 16 destroyers with this modification, with plans to upgrade 6 more by 2013.

The radar has been one of the issues. The SPY-1D radar is being used by the AEGIS weapons system is nearly two decades old. The DDG-1000 is using a Dual Band Radar (DBR), which consists of SPY-3 radar working in conjunction with a Volume

Search Radar (VSR). These two arrays are very large and heavy, which prevents them from being backfit onto a DDG-51 (Pike, 2008h; Raytheon, 2008; Scott & Janssen, 2003).

Another radar, the Advanced Missile Defense Radar (AMDR), is currently in the concept evaluation stage. This system will be the next step in technology, providing a more capable ship defense radar that will work with the AEGIS system and enhance the BMD capability. Unfortunately, this system is classified and cannot be discussed in greater detail. To account for it within the design of this lengthened DDG-51, conservative estimates are used for its size, weight, and power requirements.

New missiles are also being designed to replace the current arsenal. The aging Tomahawk will be replaced by new cruise missile with higher top speeds and longer range. The Standard Missile series will be replaced with a newer missile more suited to the BMD mission. Though data on these new missiles is classified, the assumption can be made that the new missiles will be larger and heavier. These missiles will also need a new launcher system.

As previously discussed, the MK-41 VLS system is the current standard throughout the fleet. The DDG-1000 uses a MK-57 VLS, where the missiles are not stored in a large boxlike cell that is found on the centerline of the ship, but rather in thin, long sets located around the deck edge. This is know an a periphery launcher; its design intention being that the missiles be placed along the edges to free up that large, centrally located volume they would normally occupy. The peripheral system also decreases the DDG-1000's vulnerability to a single hit (Pike, 2005e).

The MK-57 VLS uses a cell that is one missile deep and four wide, whereas the Mk-41 is a two missile deep, four wide system. The MK-57 is also much larger than the current VLS so that it can accommodate future missiles. These launchers are easily configurable to be set up like a DDG-51 class VLS where there is a large group of cells on centerline (Pike, 2005e).

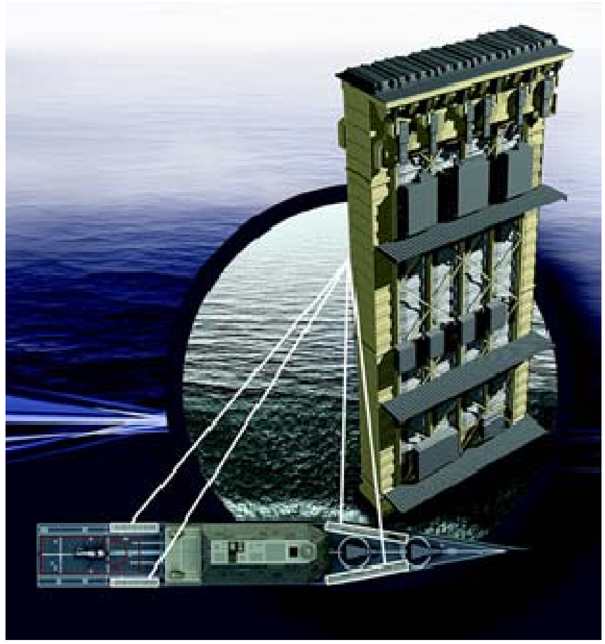


Figure 22. MK-57 VLS on DDG-1000 (From BAEinfo,2009)

The DDG-1000 was also designed with a larger, more powerful gun. The Advanced Gun System (AGS) was designed to provide high-volume, sustainable fires in support of amphibious operations and the joint land battle. The AGS utilizes a 155mm round, roughly 6.1 inches in diameter, versus the 127mm diameter of the standard five-inch projectile that is currently on the DDG-51 class. AGS was also designed to use a 155mm variant of the ERGM round, which offered a range in excess of 60 miles (Pike, 2005f).

The AGS also uses an automated magazine, greatly reducing its size and manpower requirements as compared to the 5-inch gun. Capable of a sustained fire of 12 rounds per minute, the gun can change firing angle to enable six shots to simultaneously impact at the same time on the same target. This gun will greatly increase the lengthened destroyer variant's ability to conduct STW and NSFS for forces ashore (Pike, 2005f).

Figure 23. Artist Rendition of the AGS on DDG-1000 (From Pike, 2007a)

C. CHAPTER SUMMARY

In this chapter, the legacy weapon and sensor systems from the DDG-51 Flight IIA were briefly described. Each of those systems, or a modern version of each, would be utilized on the lengthened DDG variant. By not making any drastic changes to the weapons that accomplish the missions of this vessel; costs regarding the design, construction, and crew training will be minimized. Modern technology and the ability to upgrade will be used to its fullest, making sure this variant will be at the cutting edge for its entire life.

IV. LENGTHENING ANALYSIS

A. INTRODUCTION

One key characteristic of a surface combatant is the length to beam ratio, L/B. This ratio greatly affects the resistance characteristics of a semi-displacing hullform, such as a destroyer. There are important tradeoffs between a narrow and wide ship, creating significant changes in the stability, resistance, arrangements, and seakeeping of the vessel. The purpose of this thesis is to evaluate the characteristics of a lengthened DDG-51 variant and compare it to the baseline DDG-51 Flight IIA.

The current DDG-51 Flight IIA has a length of 154 meters and a beam of 20 meters, creating an L/B ratio of 7.7. Instead of doing a full optimization to determine what would be the perfect length, other surface combatant designs are evaluated in this chapter to determine one specific length to be added to the existing DDG Flight IIA hull. By comparing these different hulls and the missions that the vessel is able to accomplish, a desired L/B ratio is determined. By taking this L/B ratio and assuming that the beam will not be changed on this DDG-51 variant, the new length is calculated.

The analysis of other ships will not be biased only towards surface combatants with L/B ratios larger than 7.7, but rather a diverse selection that shows some ships that have a ratio even lower than that of the DDG-51. The L/B ratios from all of these different ships will be averaged together to provide an initial L/B ratio, which will be used to calculate the new DDG-51 variant length. As other information from the research is factored into this evaluation, the ratio length can be increased or decreased where appropriate.

B. U.S. NAVY SURFACE COMBATANTS

The other two surface combatants that the U.S. Navy operates are the TICONDEROGA class cruiser and the OLIVER HAZARD PERRY class frigate. The TICONDEROGA is actually a cruiser version of the older SPRUANCE class destroyer,

the same hull form was re-used and turned into the AEGIS capable cruiser. The TICONDEROGA has a length of 161.24 meters and a beam of 16.76 meters, giving an L/B of 9.62 (Navy, 2009b). The TICONDEROGA carries the same SPY-1D radar, VLS system, SQS-53 sonar and various other systems as the ARLEIGH BURKE. One of the only visible differences between the DDG-51 and the cruiser is that the TICONDEROGA has two 5-inch deck guns vice only one on the destroyer. These two ships are nearly equal in their mission capabilities. Figure 24 shows an ARLEIGH BURKE and TICONDEROGA tied up to a pier side-by-side, clearly showing how much wider the destroyer is compared to the cruiser.

Figure 24. TICONDEROGA and ARLEIGH BURKE Pierside. (From Google Maps, 2010)

The PERRY class frigate is a much smaller ship, at only 126.5 meters in length and 13.72 meters in length, but is still offers another point for comparison (Navy, 2009a). This vessel does not have the same sized propulsion system, only utilizing one shaft powered by two LM-2500 gas turbine engines. Even with half the power of the DDG-51, the frigate is able to make a top speed of 29 knots, only one knot less than the destroyer. Though the mission capability is less, this frigate is still a vital ship within the U.S. Navy fleet. With an L/B of 9.22, the PERRY is another example of a ship narrower than the ARLEIGH BURKE.

The DDG-1000 may not be constructed yet, but as one of the most modern designs available, it shows what the newest trend in ship design is. The new destroyer has a length of 182.9 meters and a beam of 24.6 meters, giving a ratio of 7.43, which is significantly lower than the DDG-51 (Navy, 2010). This may be a result of the new tumblehome bow; where the shape is nearly an inversion of the standard ship bow. The DDG-1000 carries the next generation of DBR, whose large arrays demand large amounts of the upper deck space and are extremely heavy. This high center of gravity may force the beam to be wide enough to provide more stability.

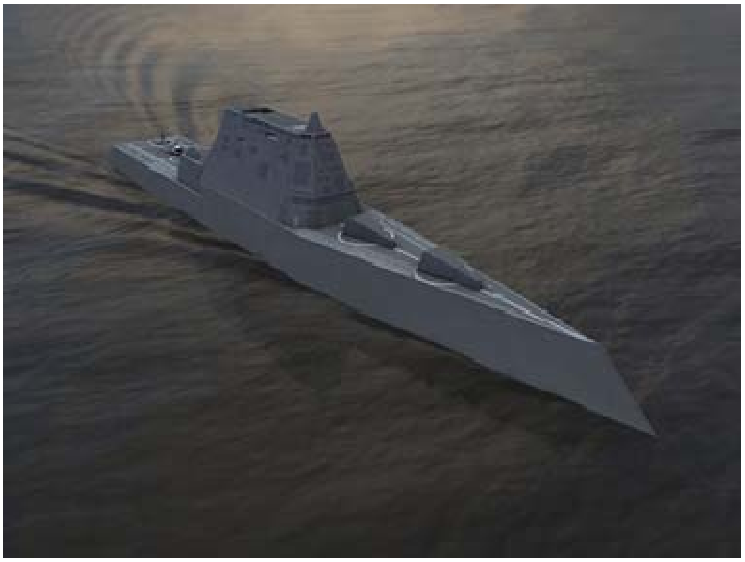


Figure 25. Artist's Rendering of the DDG-1000 (From Pike, 2008b)

C. BRITISH SURFACE COMBATANTS

As a close ally to the United States, the British and their Royal Navy has always had a comparable fleet. The Royal Navy relies heavily on smaller frigates, but also uses some larger air defense destroyers. Although these ships are generally not as capable as the DDG-51 Flight II, lacking systems like the VLS and SPY-1D, they still represent a resource to understand the range of various L/B ratios for a surface combatant.

The Type 22 frigate is a 14 ship class that was produced in three batches, similar to the Flights of the DDG-51. The Type 22 displaces between 4100–5300 ltons, roughly half that of the ARLEIGH BURKE. It has a length of 148.1 meters and a beam of 14.8 meters, giving it an L/B of 10 (Pike, 2009a). This ship does not have nearly the mission capability of the DDG-51, but does show how some designs can be extremely narrow.

Another type of British frigate is the Type 23, with a length of 133 meters and a width of 16.1 meters, an L/B ratio of 8.26 (Pike, 2009b). This frigate may be shorter than the Type 22, but it does have a forward VLS-like launcher, but does not have the large radar arrays. This ship's primary mission is ASW, and as part of this mission requirement the propulsion plant was designed to be combined electric and gas turbine. This was the Royal Navy's first investment into electric drive since the 1920s.

The Type 42 is the Royal Navy's main destroyer, with a displacement of 4100 ltons. At 141 meters long and 15.2 meters wide, her L/B ratio is a narrow 9.28, slightly smaller than the Type 22 frigate. The Type 42 is the oldest class in the British fleet, but one important design aspect is that the Batch 3 vessels were lengthened by 16.1 meters. This addition of length improves the ship's seakeeping, increases survivability by creating space between the forward weapons, and increases the length of the aft flight deck. The Type 42, Batch 3 ships shows that an older class can be improved through lengthening the hull to extend the life of the class and the mission capability. The Batch 3's L/B ratio is 10.33 (Pike, 2007c).

The Royal Navy is also constructing a new destroyer, the Type 45. Meant to replace the Type 42 as the main anti-air destroyer, it is a much larger vessel, displacing 7,300 ltons. This new destroyer is similar to both the DDG-51 and DDG-1000 class vessels; including such design features as a faceted clear deck to decrease radar cross section, a forward VLS, and a combination of both fixed array and rotating radars. The Type 45 is also a relatively wide vessel at 152.4 meters in length and 21 .2 meters wide, giving an L/B ratio of 7.19 (Pike, 2009c).

Figure 26. Type 45 Air Defense Destroyer (From Pike, 2009c)

D. AUSTRALIAN SURFACE COMBATANTS

Another close ally to the United States is Australia and their Royal Australian Navy (RAN), who has been a partner in Navy exercises and operations since World War II. Though their fleet only has 12 "blue water" surface combatants, they represent one of the most capable navies in the Pacific. Their fleet is comprised of two frigates, one of which is a copy of the U.S. designed PERRY class frigate. The Australians made no changes to the fundamental design, so the dimensions and L/B ratio are the same.

The newer ANZAC class of frigates is actually the German Meko 200 class that was licensed to be constructed in Australia. These frigates contain sophisticated radar, a MK-41 VLS, a 127mm gun, and helicopter; making them nearly as capable as a DDG-51 destroyer. The ANZAC is 118 meters long and 14.8 meters wide, an L/B ratio of 7.7 (Royal Australian Navy, n.d.).

E. JAPAN SURFACE COMBATANTS

Japan has a surprisingly large fleet, which falls under their Maritime Self Defense Force (JMSDF). The JMSDF has many different classes of both large surface combatants, grouped into helicopter and guided missile destroyers, with only a few

vessels in each class. The helicopter destroyers have a much greater beam than any other ship evaluated in this comparison and resemble smaller versions of the U.S. Navy's LHA and LHD class of amphibious assault vessels.

The JMSDF has three classes of guided missile destroyers that are comparable to the DDG-51 class. The HATAKAZE class is comprised of two ships and is the oldest in the fleet, with plans to decommission them in the next 10 years. These ships carry antiquated radar and fire control systems, but are armed with ASROC launchers, 2-5inch guns, and a vertical rail missile launcher on the forward deck. At 150 meters long and 16.4 meters, the hull has a ratio of 9.15 (Pike, 2010).

The KONGO class destroyer is a licensed DDG-51 hull form where the JMSDF designed the superstructure and other arrangements. This is the first foreign navy to be allowed to use an AEGIS fire control system. The ship is also outfitted with the latest baseline of AEGIS as well as SPY-1D radar arrays. It carries a similar complement of weapons as the Flight I ARLEIGH BURKE destroyers (Pike, 2010).

Following the KONGO class are the ATAGO class destroyers. These are a lengthened and improved version of the KONGO, incorporating helicopter hangars similar to the ones used by the DDG-51 Flight IIA. These ships have a length of 170 meters and a beam of 21 meters, giving an L/B ratio of 8.09. Since the baseline for this class is the DDG-51 hull form, it demonstrates that the vessel does have the capacity to be lengthened to create a more capable ship (Pike, 2010).

F. ANALYSIS OF VARIANT LENGTH

The above examples show a diverse set of vessels, all with similar attributes and capabilities of a DDG-51 class destroyer. From this data, a decision is to be made on how much to lengthen the DDG-51 destroyer. All of the previously mentioned ships are summarized in Tables 8, 9, and 10.

Table 8. L/B Ratios for U.S. Navy Vessels

	U.S. Surface Combatants				
Class	BURKE	SPRUANCE	TICONDEROGA	PERRY	DDG-1000
Type	Destroyer	Destroyer	Cruiser	Frigate	Destroyer
Length	154.00	161.24	161.24	126.49	182.90
Beam	20.00	16.76	16.76	13.72	24.60
L/B Ratio	8.56	9.62	9.62	9.22	7.43

Table 9. L/B Ratios of Royal Navy Vessels

	Royal Navy			
Class	Type 23	Type 22	Type 42	Type 45
Type	Frigate	Destroyer	Destroyer	Destroyer
Length	133.00	148.10	141.00	152.40
Beam	16.10	14.80	15.20	21.20
L/B Ratio	8.26	10.01	9.28	7.19

Table 10. L/B Ratios of Australian and Japanese Vessels

	RAN	JMSDF		
Class	ANZAC	HATAKAZE	KONGO	ATAGO
Type	Frigate	Destroyer	Destroyer	Destroyer
Length	114.00	150.00	161.00	170.00
Beam	14.80	16.40	21.00	21.00
L/B Ratio	7.70	9.15	7.67	8.10

To provide an initial estimate of what the new DDG-51 length should be, all of the length to beam ratios are averaged, giving a value of 8.53 with a variance of 1.245. When this value is used to determine the new DDG-51 length, the ship is 170.7 meters long, resulting in a lengthening of 16.7 meters. After considering such factors as increased mission capability and larger weight margins for future upgrades, this initial L/B ratio estimate of 8.53 is increased slightly to 8.6. This increases the ship to 172 meters and results in an 18-meter extension.

Another important question in this design is how to incorporate this 18 meter extension. One way could be through the use of a parallel mid-body section. This is where the ship is split, usually at its maximum beam, and a parallel section of hull is inserted. Another way is to equally change all the hull length dimensions, which would change the stern and bow shapes. A third method of lengthening the ship is to insert smaller sections of the extension throughout the hull.

Since cost is such a factor with new ship design and construction, one of the easiest ways to lengthen this DDG variant would be to use the parallel mid-body method. The two shipyards currently producing the DDG-51 have jigs and stands already designed around the specific curvature of the bow and stern. By utilizing as much from the prior hull form as possible, the shipbuilders would not have to invest in the capital of new jigs and retain as much of their modular build methodology. It is decisions like this that could significantly affect the construction costs of any modified repeat of a ship class.

G. CHAPTER SUMMARY

Different U.S. and foreign ship designs are evaluated to understand the diverse length to beam ratios that currently exist. These are compared and analyzed to determine an average L/B ratio of 8.53. Mission consideration and other factors suggest that the ratio be increased to 8.6, resulting in a modified repeat DDG-51 that is 172 meters long and 20 meters wide. The hull extension will be incorporated into the current hull form by utilizing a parallel mid-body; this will help keep redesign and construction costs at a minimum.

V. HYDROSTATICS, RESISTANCE AND PROPULSION

A. INTRODUCTION

The first analysis will be to compare the hydrostatic characteristics between baseline DDG-51 Flight IIA and the lengthened variant. This comparison will be of the physical characteristics of the two ships; the dimensions and the geometry that has significant effects on the resistance, propulsion, and seakeeping.

The analysis focuses primarily on the hullform and the resultant centers of buoyancy. There are no calculations performed concerning the centers of gravity since that requires a more detailed design effort of the ship systems, which is not the intent of this research.

There are some key terms that describe the basic dimensions and characteristics of a ship. The ship's length is represented by the Length on the Waterline (LWL) and the Length Over All (LOA). The width is represented by the Beam (B) or Beam on the Water Line (BWL) and the depth to the keel, or draft, is defined as T. These basic dimensions are represented in Figures 27 and 28.

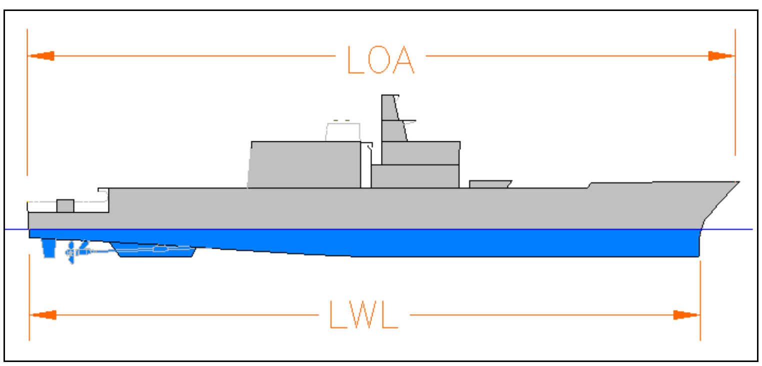


Figure 27. Drawing Showing the Ship Length Nomenclature (From Wikipedia, 2010a)

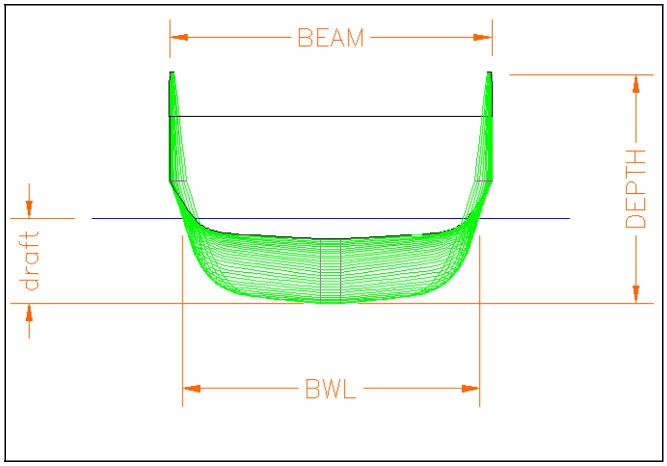


Figure 28. Drawing Showing the Nomenclature Associated with the Beam (From Wikipedia, 2010a)

B. HYDROSTATIC COMPARISON

The dimensions of the baseline DDG-51 and those of the lengthened variant is shown below, the 18-meter addition did not affect all the basic ship characteristics.

Table 11. Comparison of the Basic Dimensions of the Two Destroyers

	DDG-51 FLT IIA	DDG Lengthened Variant
LOA (m)	154	172
LWL (m)	144.68	162.68
Keel Draft (m)	7	7
Beam (m)	20	20
BeamWL (m)	18.51	18.51
Displacement (ltons)	9498	11500

Table 11 shows that the only dimension change is the lengthening of 18 meters to the LOA and LWL. Due to the change in length, the displacement of the lengthened DDG-51 variant increased by ~2000 ltons, putting it close to the size of the DDG-1000 at 14,500 ltons. The displacement is determined by using a Computer Aided Design (CAD) program called Rhinoceros (Rhino). Rhino has a naval architecture module within it that

is able to calculate many of the necessary dimensions and characteristics of the hullform. The waterline in this module is initially estimated and then altered to equal the full load displacement of the known DDG-51 Flight IIA. Then this same keel draft is used to calculate displacement of the lengthened variant.

C. COEFFICIENTS

The dimensions from Rhino are then used to calculate important coefficients needed for the resistance calculations. These coefficients are non-dimensional descriptions for the shapes of the two ships. The coefficients also have standard 'rules of thumb' that can predict how a ship will behave hydrodynamically.

The Block Coefficient (C_B) is the volume (V) of the ship divided by the LWL x BWL x T, the ratio of the volume of the ship divided by the box that the dimensions of the ship creates. A larger C_B means that the ship has a fuller form and nearly fills the box, whereas a smaller CB describes a vessel with slimmer bow with more flare and a shallower stern

$$C_B = \frac{V}{LWL * BWL * T} \tag{1}$$

The Midship Coefficient (CM) is the cross-sectional area (AM) of the midship of the vessel divided by the BWL x T. This is the ratio of the largest underwater transverse area to the rectangle of the same height and width. This defines the fullness of the underwater body that must move through the water. A low C_M indicates a slender mid-section whereas a high C_M indicates a boxy section shape. For example a tanker will have a very high C_M and a speedboat will have a relatively low value.

$$C_M = \frac{A_M}{BWL * T} \tag{2}$$

The Prismatic Coefficient (C_P) is the volume (V) divided by LWL x A_M, the ratio of the underwater volume of the hull to the volume of the A_M extruded for the length of the waterline. This coefficient is used to evaluate the distribution of the volume of the hull below the waterline. A low C_P indicates a full mid-section and narrow bow and stern

sections, a high C_P indicates a boat with fuller ends. Planing hulls and other high-speed hulls tend towards a higher C_P. Efficient displacement hulls travelling at a low Froude number will tend to have a low C_P. The Froude number is the ratio of inertia over gravitational forces and is used to quantify the resistance of a vessel moving through water.

$$C_P = \frac{V}{LWL * A_M} \tag{3}$$

$$C_P = \frac{C_B}{C_M} \tag{4}$$

The Waterplane Coefficient (C_{WP}) is the waterplane area (A_{WP}) divided by LWL x B, which expresses the ratio of the waterplane area to a rectangle of the same length and width. A low C_{WP} figure indicates fine stern and bow section ends and a high C_{WP} figure indicates fuller ends. A high C_{WP} value usually implies better stability as well as handling behavior in rough conditions.

$$C_{WP} = \frac{A_{WP}}{LWL * BWL} \tag{5}$$

Table 12 shows the dimensions for the two vessels and their coefficients. It is obvious that the DDG-51 lengthened variant will have a larger volume and waterplane area, but since there is no change to the beam the midship area did not change. Some of the coefficients show nearly a 10 percent increase between the baseline DDG-51 and the lengthened variant after an 11.6 percent increase in length.

Table 12. A Comparison of the Two Vessels Hydrostatic Coefficients

	DDG-51 FLT IIA	Lengthened DDG Variant
Volume Displacement (m^3)	9495.96	11413.70
Longitudinal Center of Buoyancy (m)	72.83	81.84
Wetted Surface Area (m^2)	3032.18	3505.93
Water Plane Area (m^2)	2120.62	2452.14
Longitudinal Center of Floatation (m)	78.53	87.57
Midship Area (m^2)	107.21	107.21
Block Coefficient	0.5066	0.5415
Midship Coefficient	0.8275	0.8275
Prismatic Coefficient	0.6122	0.6544
Waterplane Coefficient	0.7919	0.8144

From Table 12, it appears that the lengthened DDG variant will have slightly high speeds due to the larger prismatic coefficient and be more stable based upon the larger waterplane coefficient differences in the coefficients. The coefficients will also be used to help calculate the resistance and propulsion of the two vessels.

D. RESISTANCE

The resistance and propulsion data is created using software from the University of Michigan called Power Prediction Program (PPP). Input values include the dimensions of the vessel, the hull coefficients, and factors representing the drag caused from appendages. The program outputs a variety of resistance values, required thrust, and the required power to achieve a specified speed.

The total resistance of a ship is comprised of three types of resistance; the viscous resistance, the wavemaking resistance, and the resistance cause by the superstructure. The total resistance, in Newtons, is multiplied by the speed, in meters per second, to calculate the required power in Watts.

Viscous resistance is due to the viscous stresses that the seawater exerts on the hull. The factors that can affect the viscous drag include the viscosity of the water, the ship's velocity, the wetted surface area, and the roughness of that area. The Reynolds number, a non-dimensional value, represents the viscosity, size, and speed of the vessel.

Wavemaking resistance is the drag caused by the waves a vessel creates as it moves through the water. The waves are formed due to the vessel displacing water and the water wanting to level out again. This drag is comprised of the Beam to Length ratio, displacement, shape of the hull, and ship speed. This drag is characterized by the Froude Number, another non-dimensional value.

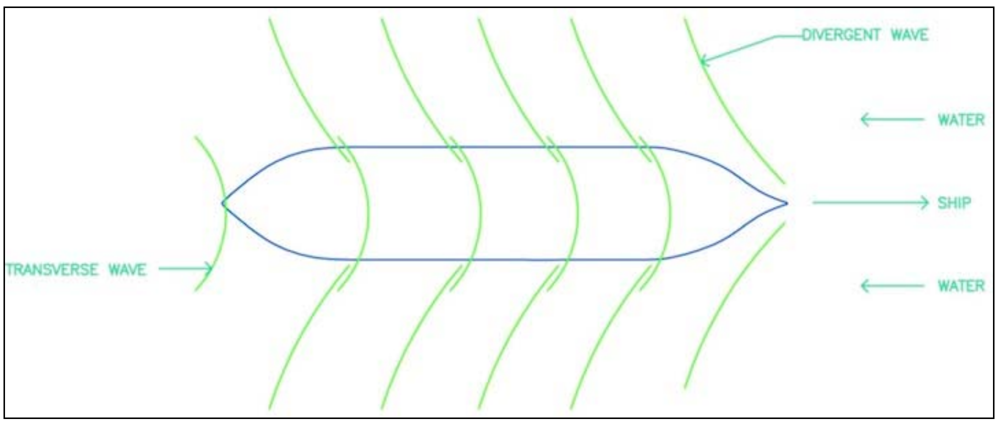


Figure 29. The Bow, Divergent, and Transverse Waves Created by Ship Motion (From Marinewiki, 2010)

The air resistance is the drag created by the above water superstructure and hull as it moves through the air. This resistance is usually very small compared to the other two forms of drag, typically between three and 10 percent. For the DDG-51 and the lengthened variant, the air drag is assumed to be the same between the two vessels since the topside design is not part of this research. The total resistance of both vessels is shown in Figure 30.

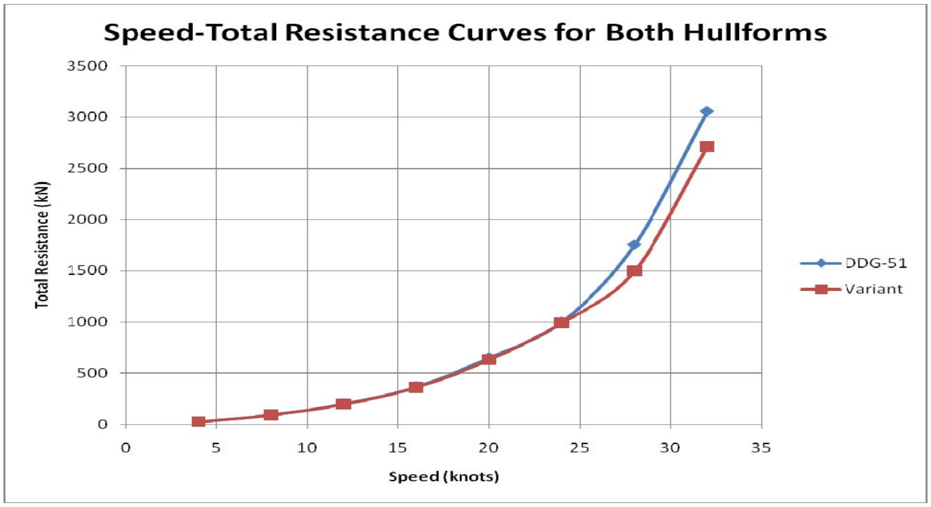


Figure 30. Plot of the Speed-Resistance Data of the Two Destroyers

This graph shows that as the the speed increases, the lengthened variant of the DDG-51 has less total resistance. Though the baseline variant has a smaller A_{WP} the increased L/B ratio of the lenghtened variant creates a lower resistance. Figure 31 shows the resistance-speed plot for three different types of hull forms. The displacement hullform is utilized by the majority of cargo ships due to their extremely efficient ‘hull speed’ or the speed just before the large increase of slope on the plot. The semi displacement hull is used for most surface combatants and other ships that require a higher top speed. The planing hullform is used for smaller craft that have higher speeds. The plot shows how the slope of the planing hull is less than that of the semi-displacement hull, just as the slope decreased on the DDG-51 variant as compared to the baseline DDG-51 Flight IIA. The increase in L/B ratio greatly reduces the total resistance.

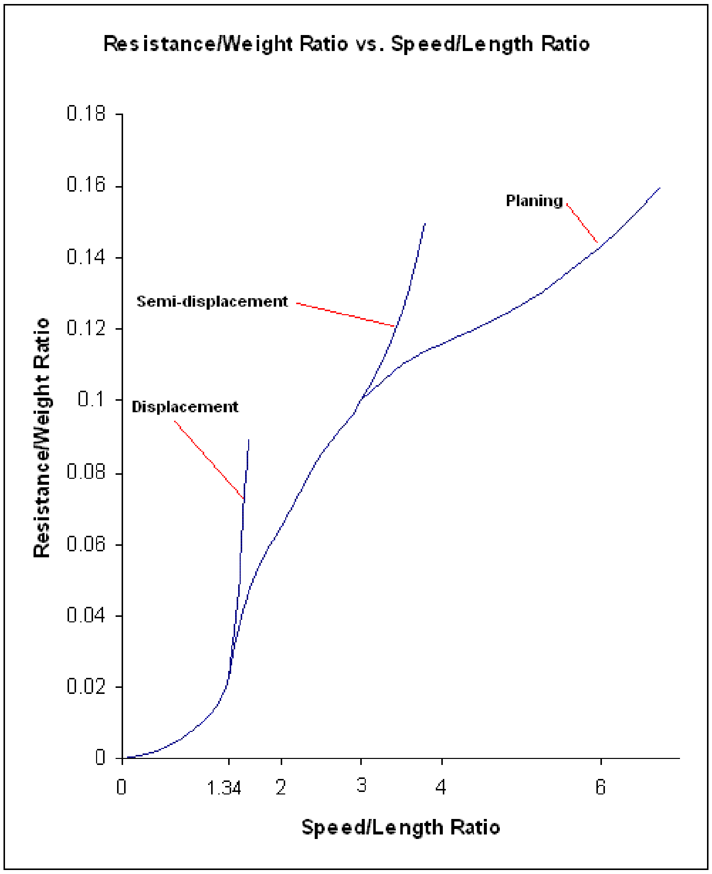


Figure 31. Speed-Resistance Plot of Different Types of Hullforms (From Wikipedia, 2009)

E. PROPULSION

The current DDG-51 destroyers have 100,000 horsepower (75MW) of power in their main engines. The system has four LM2500 gas turbine engines powering two shafts through two sets of reduction gears. The shafts spin two controllable pitch propellers that are 5.18 meters in diameter. The ARLEIGH BURKE has a maximum speed of 30 knots. For a comparison the TICONDEROGA class cruiser, which is slightly larger in displacement, only requires 80,000 horsepower to achieve the same speed due to its larger length to beam ratio. This shows how important a slender hullform is to the resistance and propulsion of a ship.

The total resistance from the previous section is used to compute the required power. PPP is able to provide an estimate for the required power necessary to propel the two destroyers at different speeds. These values are plotted from 0–32 knots, but a discrepancy between the program's data and the actual power of the DDG-51 is apparent. The program initially shows that the destroyer only needed ~45MW to achieve the 30-knot maximum speed. To account for this, a calibration factor is applied to the DDG-51 data from PPP to ensure that the plot matched the 75MW, 30-knot data point.

This calibration factor is also applied to the data of the lengthen DDG-51 variant. This calibration factor can represent many different inefficiencies of the propulsion system, such as the propeller, bearings, shaft seals, and reduction gears. The data from PPP is only the power the propellers have to impart on the water, accounting for none of these inefficiencies. A normal ship's mechanical and propeller inefficiencies are roughly 75 percent. But the calibration factor ended up being 60 percent, which is lower than expected. This may be due to an error within the PPP program. A plot comparing the DDG-51 baseline and variant is shown in Figure 32.

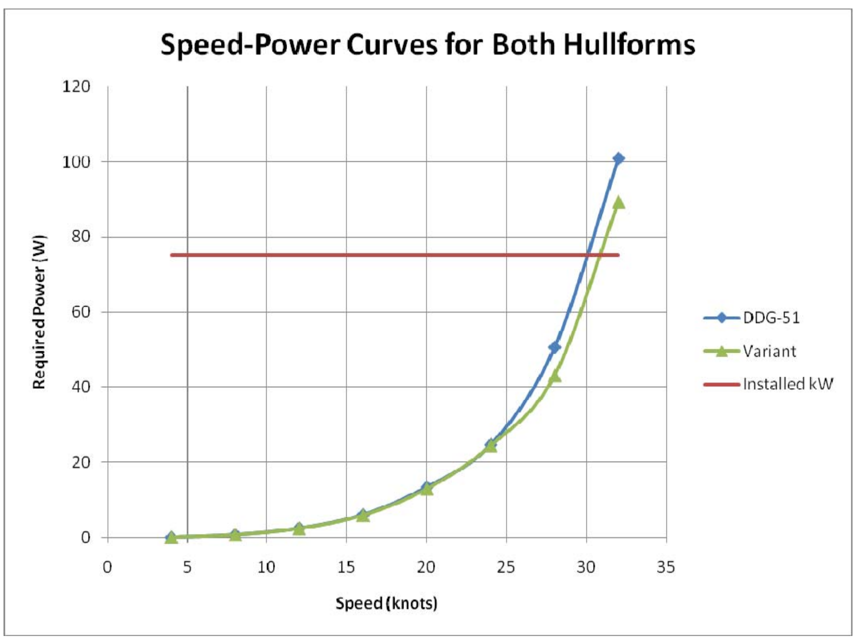


Figure 32. Speed-Power Curve of the Two Destroyers

The plot shows the installed power and the DDG-51 baseline intersecting at 75 MW and 30 knots as the known point fixed by the calibration factor. The power of the lengthened variant is 10 MW less than the baseline destroyer. This DDG-51 modified repeat can be designed with a power plant that produces only 65MW or if it retains the same power plant, can have a maximum speed of 32 knots.

The output files from PPP for the baseline DDG-51 and the lengthened variant are shown in Appendix A and B.

F. CHAPTER SUMMARY

This chapter compares the resistance and propulsion characteristics of the two destroyers. The lengthened variant has a lower total resistance and therefore needs 10 MW less power to make the notional required speed of 30 knots.

VI. SEAKEEPING ANALYSIS

A. INTRODUCTION

Seakeeping is another important design factor that will change when a ship's hull is lengthened. Ship motions can be broken down into two groups, translations and rotations. The translations and rotations are each made up of three motions associated with the three axes. Translation along the longitudinal axis is known as surge, motion in the transverse direction is sway, and vertical motion is heave. Rotation about the longitudinal axis is known as roll, the transverse axis is pitch, and the vertical axis is yaw. These motions are represented in Figures 33 and 34.

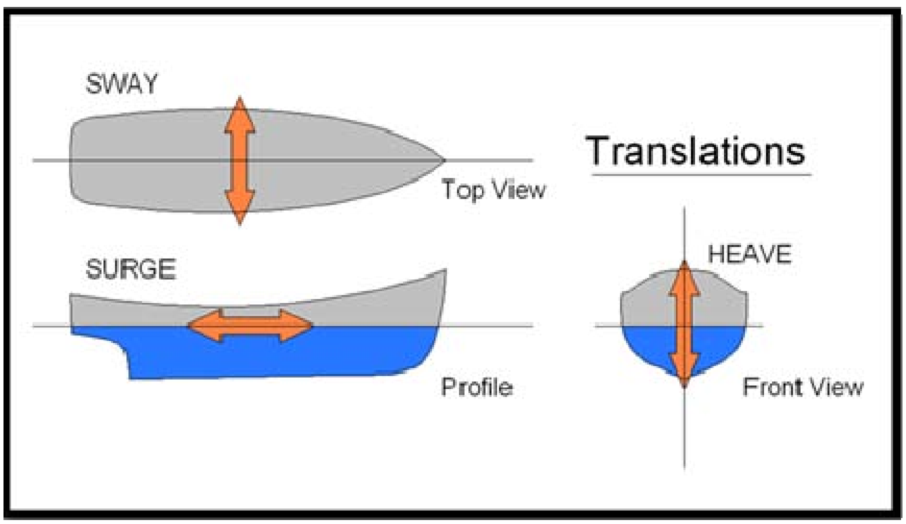


Figure 33. Ship Translation Motions (From Wikipedia, 2010b)

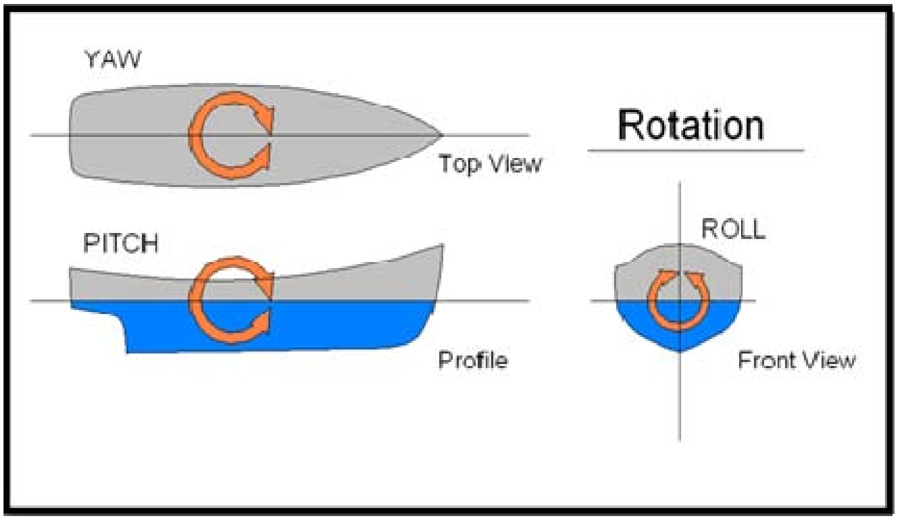


Figure 34. Ship Rotation Motions (From Wikipedia, 2010b)

Ship motions are caused by the interaction of waves and the ship. These motions are affected by the hull shape, ship speed, angle, and size of the waves. Seakeeping can impact the operations of the vessel, both through crew comfort and the fundamental ability to conduct the required missions of the ship. For a DDG-51 Flight IIA destroyer, the critical mission that the ship needs to conduct is flight operations. The greater the ability for the ship to conduct it missions in foul seas, the more capable of a surface combatant it is.

The seakeeping analysis for these two hullforms is performed using a FORTRAN program called SHIPMO. This program takes an input file consisting of the following information

- Hull offsets
- Ship Speed
- Vertical and longitudinal centers of gravity and buoyancy
- Wave height
- Relative angle of the wave to the vessel

The program performs a two dimensional strip theory analysis to determine the mass damping properties at each offset location; then sums the motions to provide the overall ship motion. The program's output files are put into both Microsoft Excel and

MATLAB to provide plots of the motion. Excel is used to create the linear plots of the ship motion where the y-axis represents the ratio of ship motion over the incoming wave height; a value of one means that the ship moved the same amount as the wave height. The x-axis represents the frequency of the incoming waves. A discontinuity in the graph represents an excitation frequency in the ship's hull.

There are also polar plots of the different ship motions provided for a variety of conditions, some listed in this section and some in Appendices C through F. These polar plots show the vessel in the ahead direction at 0° and the relative angles to the port and starboard, though the angles are reversed due to a limitation of MATLAB plotting. The radius represents speed with 0 knots at the origin and the outer radius represents 30 knots. The polar plots are also related to a specific sea state, which is based upon the Douglas Sea Scale shown in Table 13.

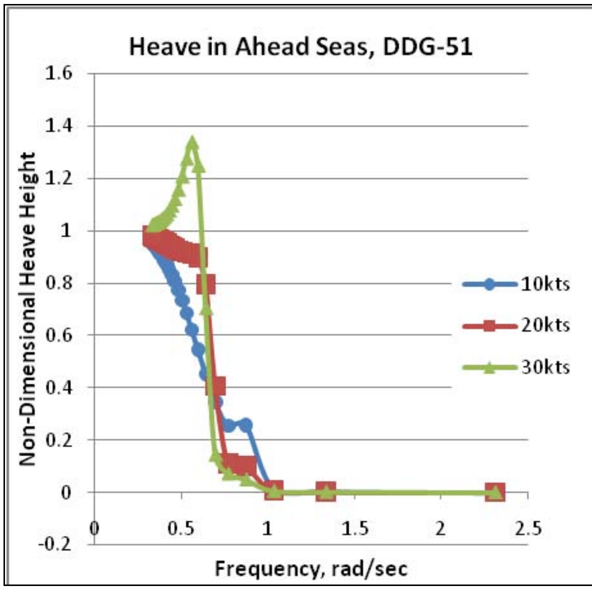
Table 13. Douglas Sea Scale Conditions

State	Height (m)	Description
0	None	Calm (Glassy)
1	0 – 0.1	Calm (Rippled)
2	0.1 – 0.5	Smooth
3	0.5 – 1.25	Slight
4	1.25 – 2.5	Moderate
5	2.5 – 4.0	Rough
6	4.0 – 6.0	Very Rough
7	6.0 – 9.0	High
8	9.0 – 14.00	Very High
9	14.0 +	Phenomenal

For the DDG-51 and the lengthened variant only a few of the motions will be explored in detail. The motions that naval architects are most concerned with are heave, pitch, and roll since these motions are the most critical to ship operations. Each of these motions is analyzed in the following sections.

B. HEAVE

The heave motion is the translation in the up or down direction, making a person feel like they are either heavy or light as the ship's acceleration increases or decreases the effect of gravity. This motion can affect the ability of a helicopter to land as the deck moves up and down, possibly causing the pilot to slam the aircraft down onto the deck. The following plots will compare the DDG-51 and the lengthened variant at three different speeds and at the five main relative angles of wave motion.



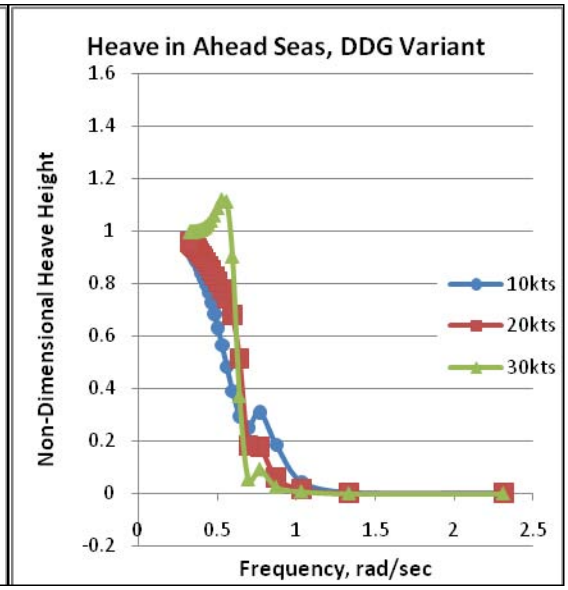


Figure 35. Heave Motion from Ahead Seas for Both Vessels

The lengthened variant has less heave motion in the ahead direction at all three speeds by over 20 percent, with the major excitation frequency at ~0.6 radians per second at 30 knots.

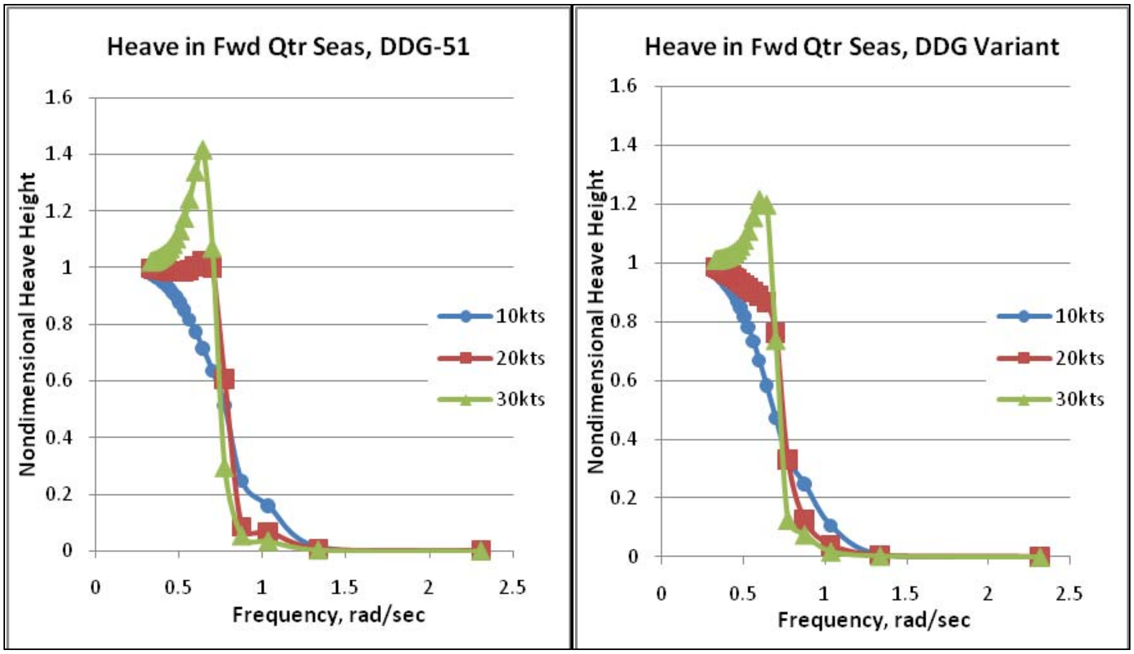


Figure 36. Heave Motion from Forward Quarter Seas for Both Vessels

In the forward quarter direction, the DDG-51 lengthened variant again outperforms the baseline DDG, with the major excitation at ~0.7 radians per second being nearly 20 percent less.

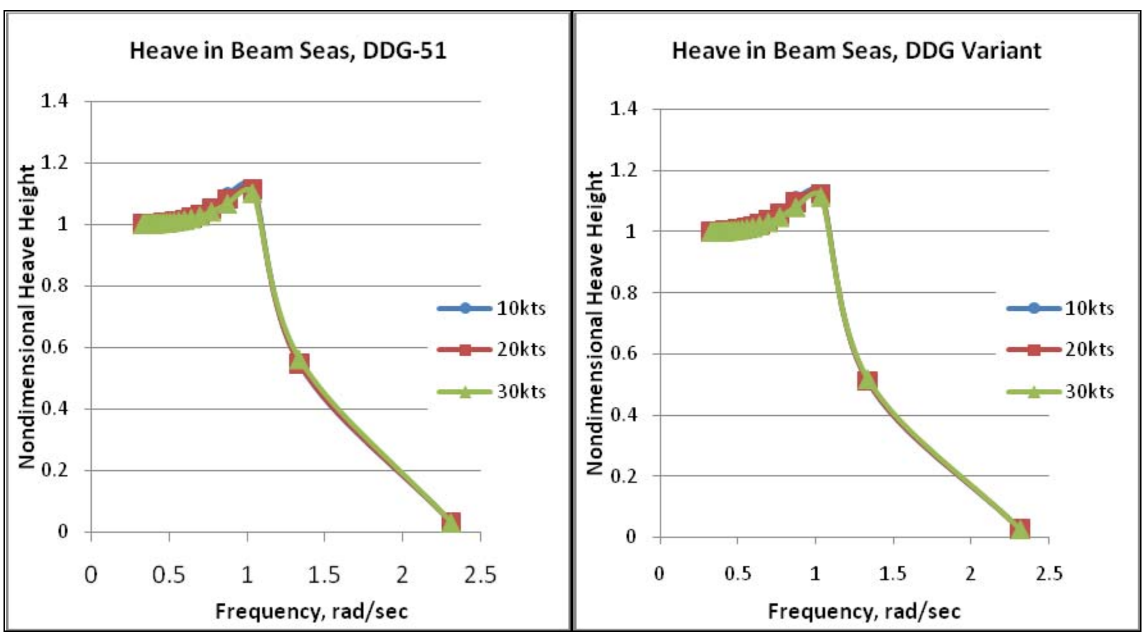


Figure 37. Heave Motion from Beam Seas for Both Vessels

In beam seas the plots are nearly identical, as expected with these two similar vessels. The lengthened hull of the variant did not impact the heave motion in beam seas.

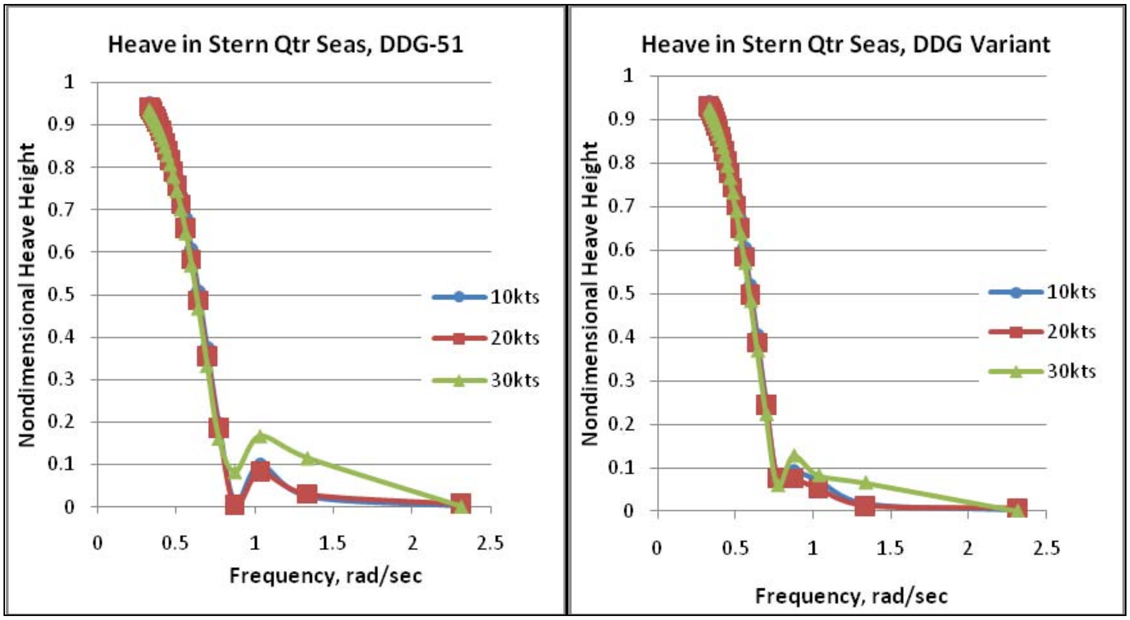


Figure 38. Heave Motion from Stern Quarter Seas for Both Vessels

The heave in stern quarter seas is not amplified in either hullform and decreases as the frequency of the wave increases.

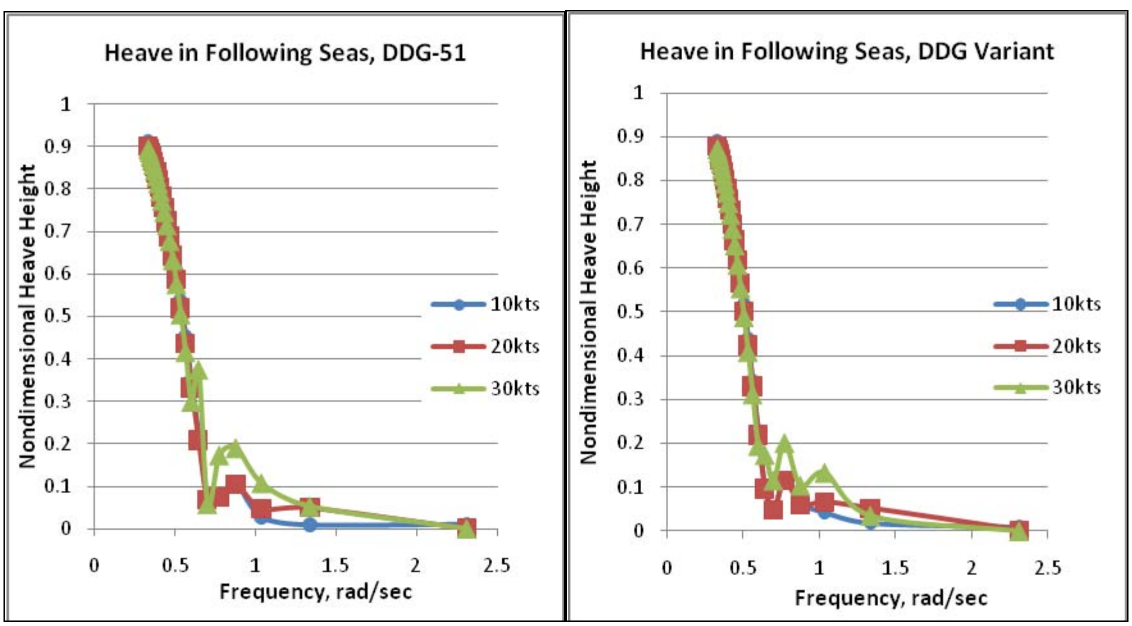


Figure 39. Heave Motion from Following Seas for Both Vessels

The following seas shows minimal heave motion, some slight discontinuities at just below one radian per second, but at only 10 percent of the incoming wave height, those motions will not affect operations.

C. PITCH

The pitch motion is the rotation about the transverse axis of the ship, the bow rising as it strikes a wave. This motion can affect the operation of the ship, but more often hinders comfort of the crew. The following graphs show the pitch motion of the vessel both in linear plots as well as polar plots.

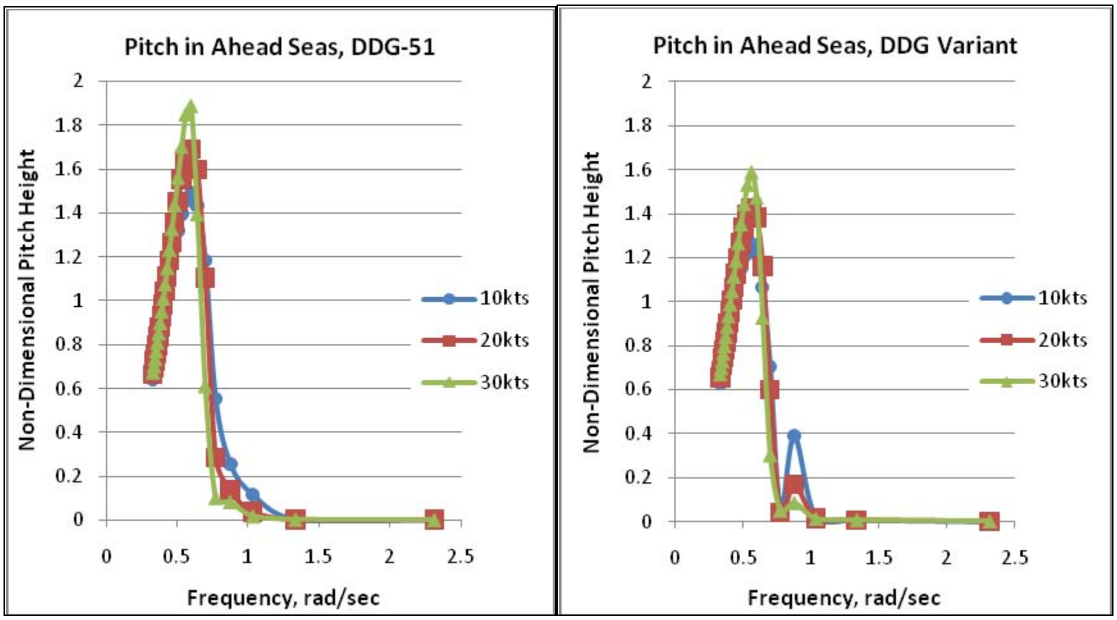


Figure 40. Pitch Motion from Ahead Seas for Both Vessels

The ahead direction is the worst for pitch as the destroyer's bow plows into each oncoming wave. The baseline DDG-51 shows an amplitude of nearly twice the incoming wave height, but the lengthened variant has an amplitude of roughly 20 percent less. The DDG-51 lengthened variant does show a second natural frequency excitation at approximately 0.9 radians per second, but the amplitude is only 0.4 of the incoming wave height.

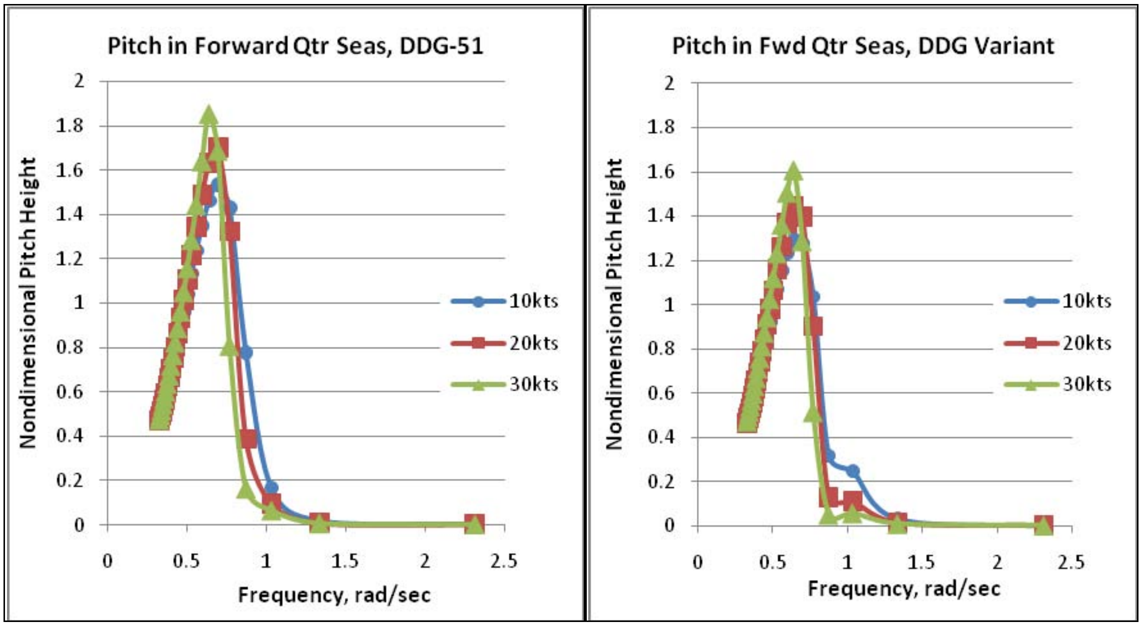


Figure 41. Pitch Motion from Forward Quarter Seas for Both Vessels

The results from the forward quarter seas are nearly identical to the ahead seas, showing that both the baseline and lengthened destroyers will have significant pitch from this direction.

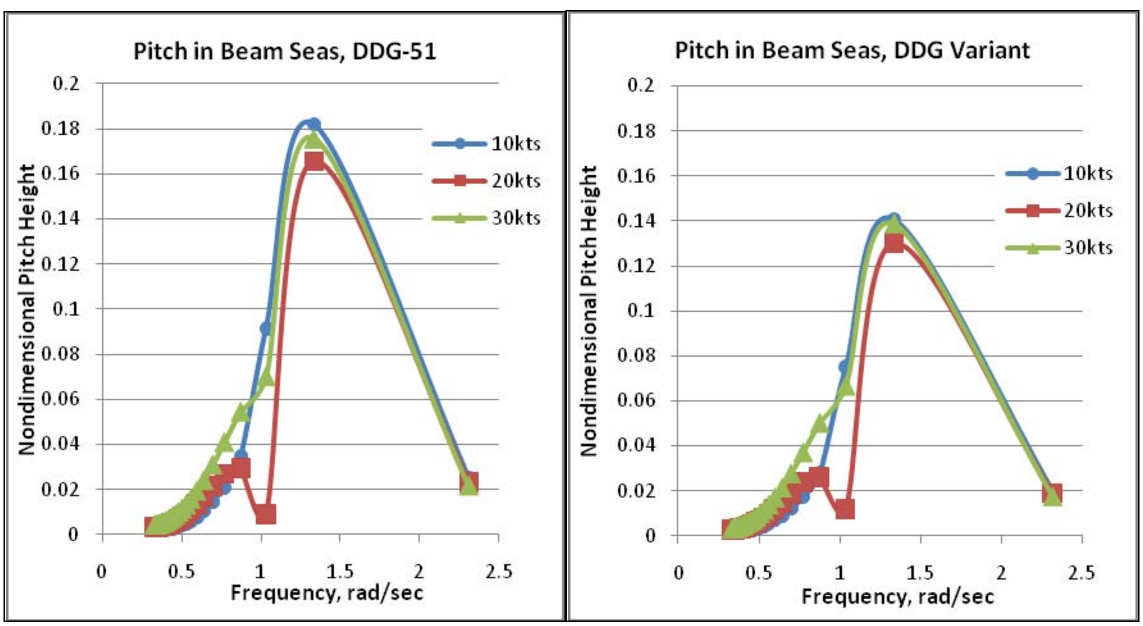


Figure 42. Pitch Motion from Beam Seas for Both Vessels

The beam seas also show that the two vessels have similar seakeeping characteristics, but the lengthened DDG variant has less amplitude.

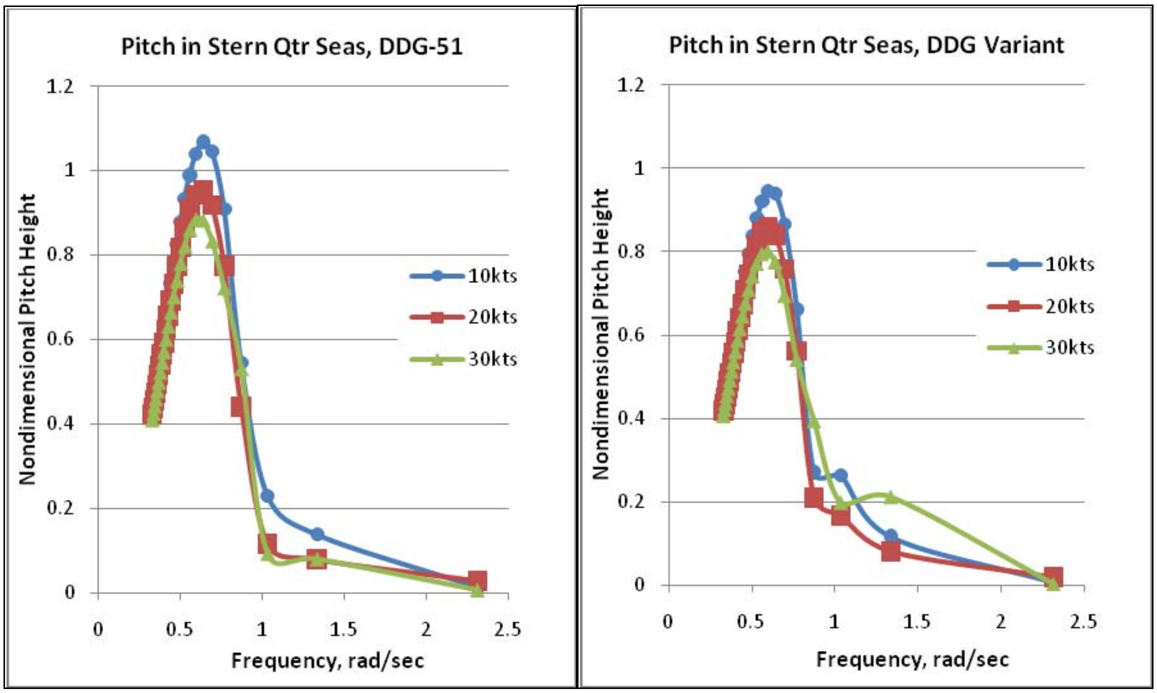


Figure 43. Pitch Motion from Stern Quarter Seas for Both Vessels

The stern quarter sea is another condition where the lengthened DDG variant has less motion than the shorter baseline DDG-51.

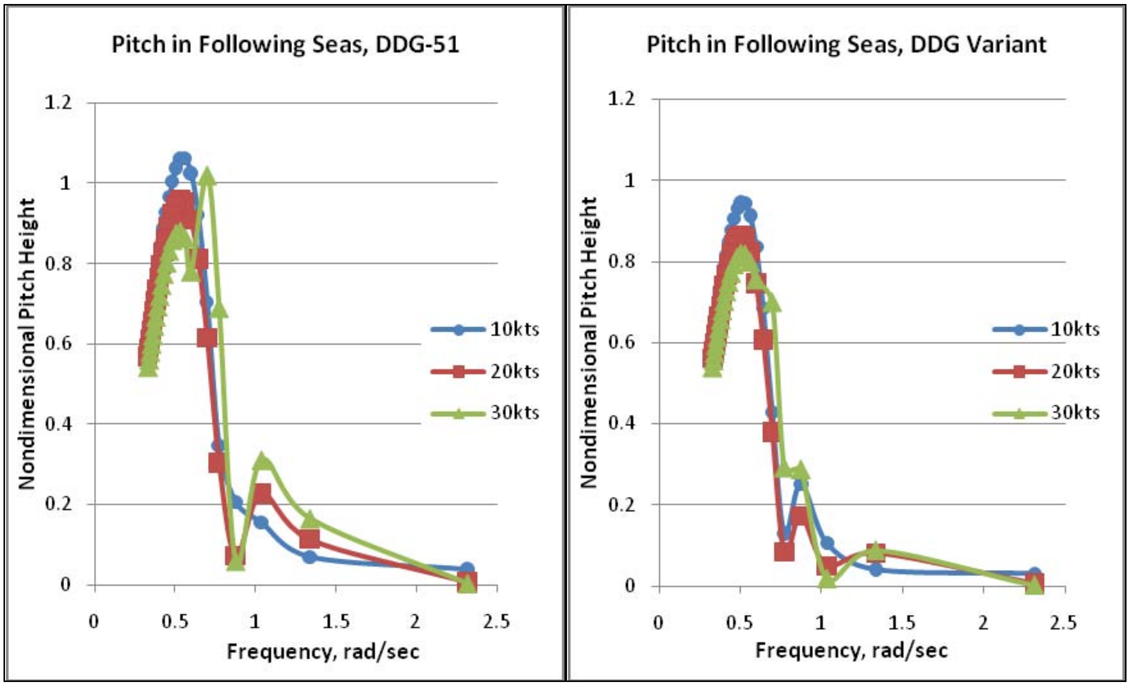


Figure 44. Pitch Motion from Following Seas for Both Vessels

The following seas condition is one that can often cause a ship to become difficult to control. These plots show that the baseline DDG-51 has a pitch motion of slightly greater than the incoming wave height, and the lengthened version slightly less. Another natural frequency occurs around one radian per second but has a lower amplitude.

The following plot shows a comparison of the two vessels at three different sea states that a destroyer will encounter. These polar plots are able to show the expected angle of pitch that the vessel will experience at the different speed, angle, and sea state conditions. For example, the baseline DDG-51 will experience pitch angles of roughly 1.8 degrees in sea state seven, taking following seas at approximately 5 knots and greater.

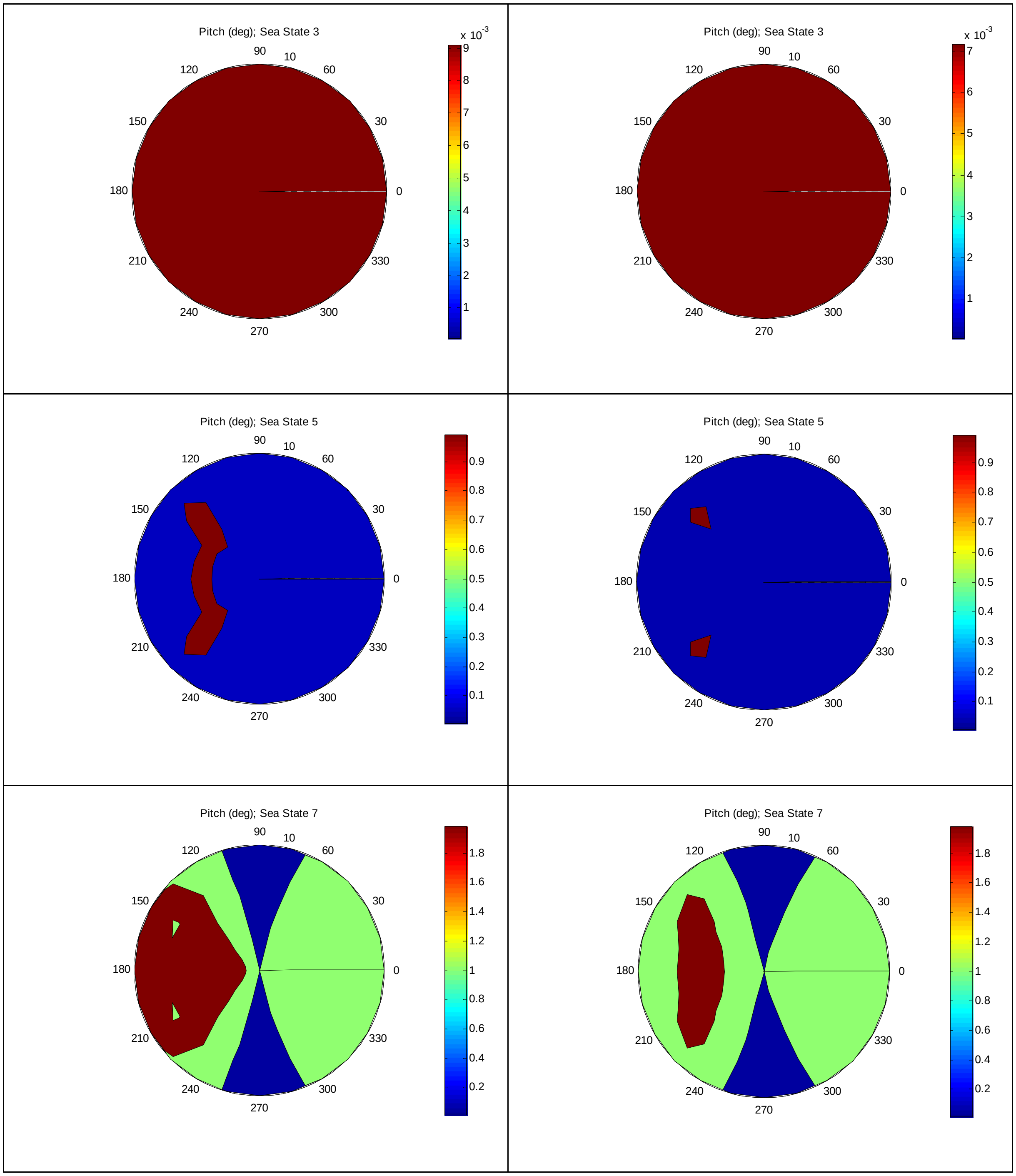


Figure 45. Polar plot of Pitch Motion of the Baseline and Lengthened Variant DDG-51 at Various Sea States

D. ROLL

The roll motion is the rotation about the longitudinal axis of the ship and is often the reason for people on a ship becoming seasick. Though this motion is mainly associated with crew comfort, rolling also has effects on the ability to conduct helicopter operations.

There are ways to counteract this motion. The current DDG-51 class destroyers have a bilge keel, an appendage to the hull along the curvature of the bilge to help reduce the amount of roll. There is also an upgrade where an automated system alters the position of the rudders to help counteract the motion. Another system that is used on cruise ships and other commercial vessel is dynamic stability fins, a set of wings that can change position to counteract the roll motion.

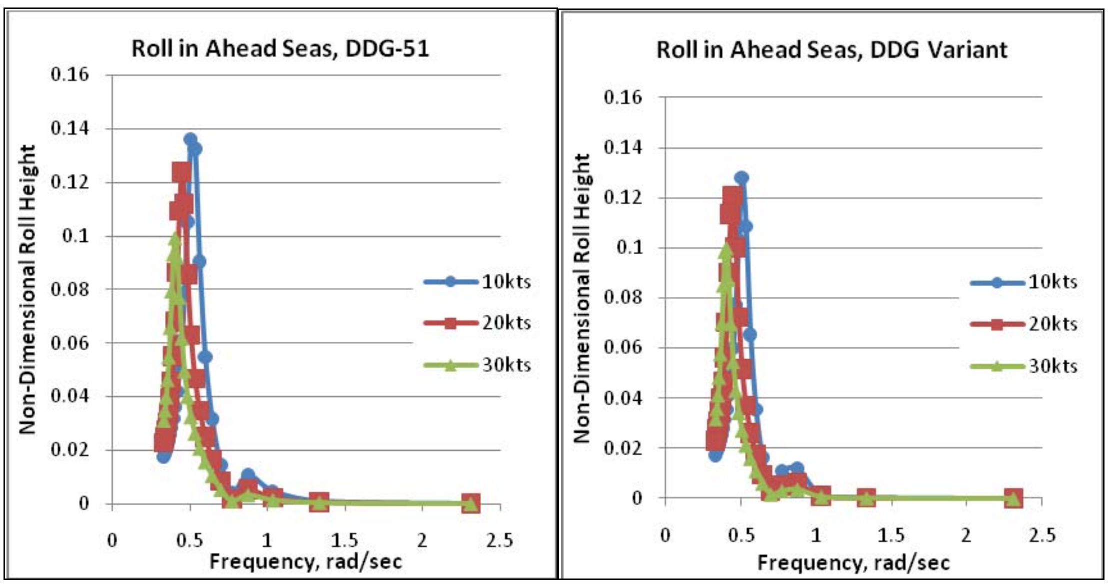


Figure 46.   Roll Motion from Ahead Seas for Both Vessels

The roll motion is minimal for both the baseline and lengthened DDG-51 hullforms, with a total amplitude of less than 14 percent of the original wave height.

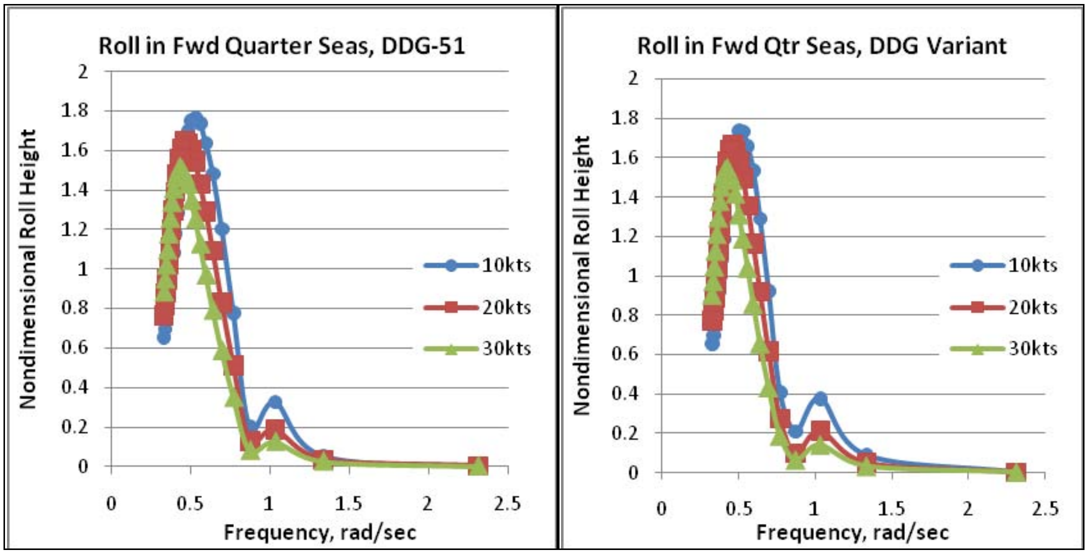


Figure 47. Roll Motion from Forward Quarter Seas for Both Vessels

The motion quickly increases as the seas are experienced on the forward quarter. The amplitude of the motion for both vessels nearly doubles from the incoming wave height.

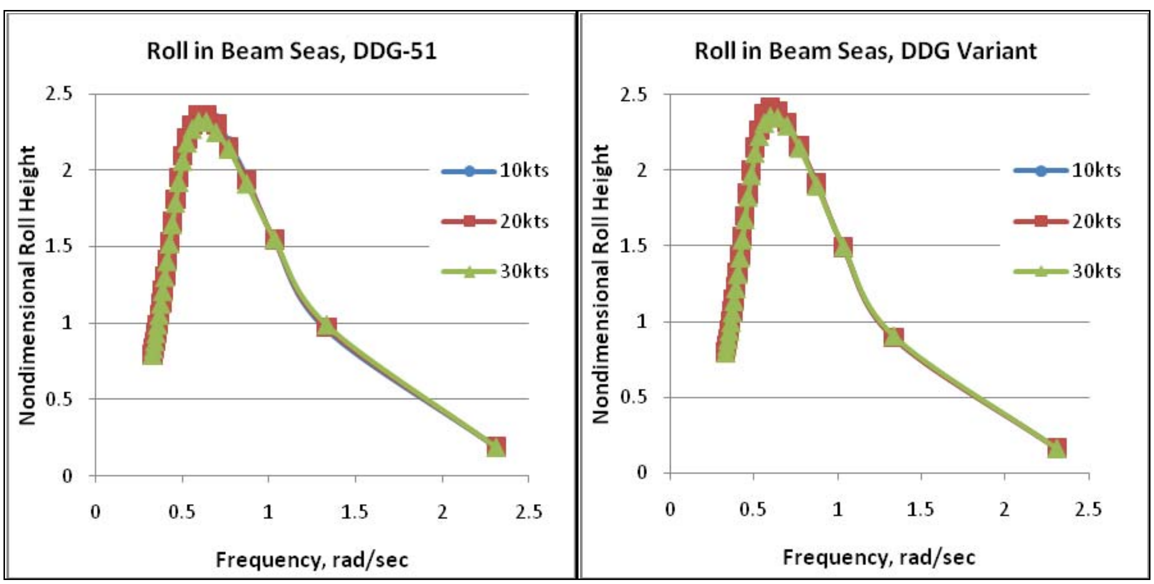


Figure 48. Roll Motion from Beam Seas for Both Vessels

The beam seas are nearly identical between the two vessels, with motion nearly 2.5 times greater in amplitude from the incoming wave height.

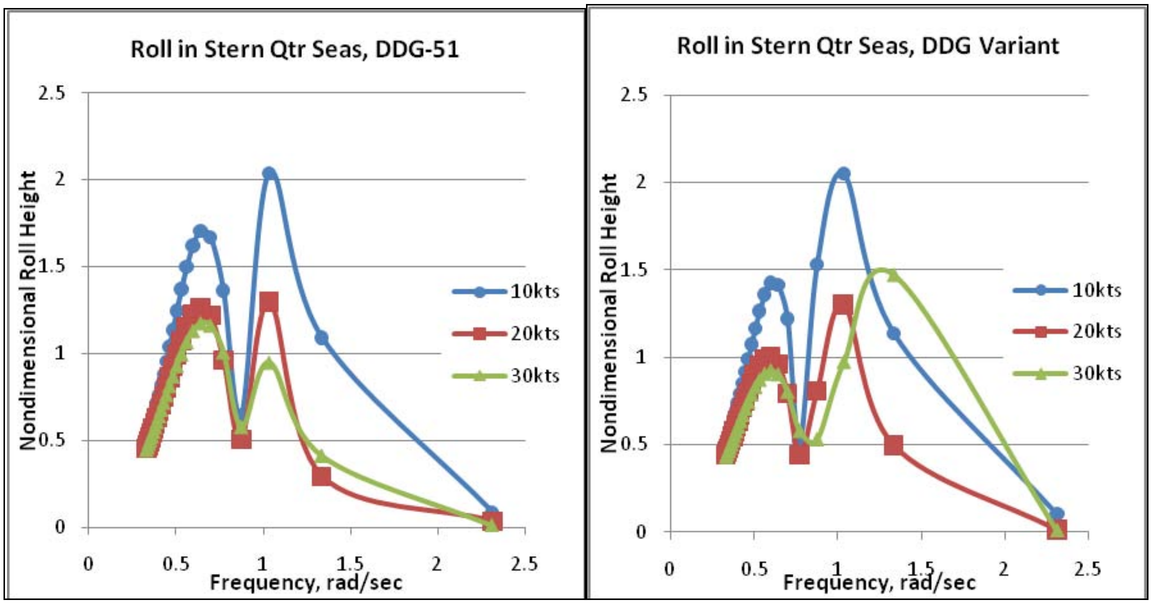


Figure 49. Roll Motion from Stern Quarter Seas for Both Vessels

These two plots look very similar between the two vessels at the speeds of 10 and 20 knots, but for the lengthened DDG variant, the data at 30 knots shows that the vessel has a large second natural frequency that does not exist on the baseline DDG-51. This difference in seakeeping can be seen in Figures 51 and 52.

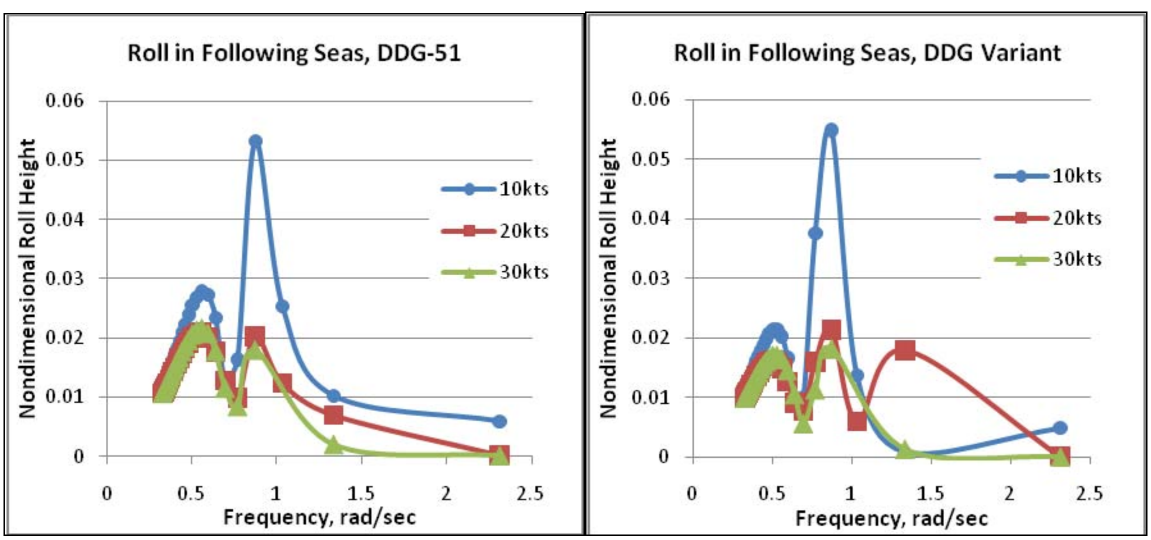


Figure 50. Roll Motion from Following Seas for Both Vessels

In following seas, the two vessels are very similar and the values of the amplitude being so relatively low can be interpreted as no roll motion.

The polar plots in Figure 51 show that the lengthened variant of the DDG-51 has more severe roll motion in the high sea states when taking seas from the forward quarter to beyond the stern quarter in a wide range of speeds. The roll exceeds 14 degrees for a large portion of the plot, which will impact the ability of the crew to operate the vessel safely.

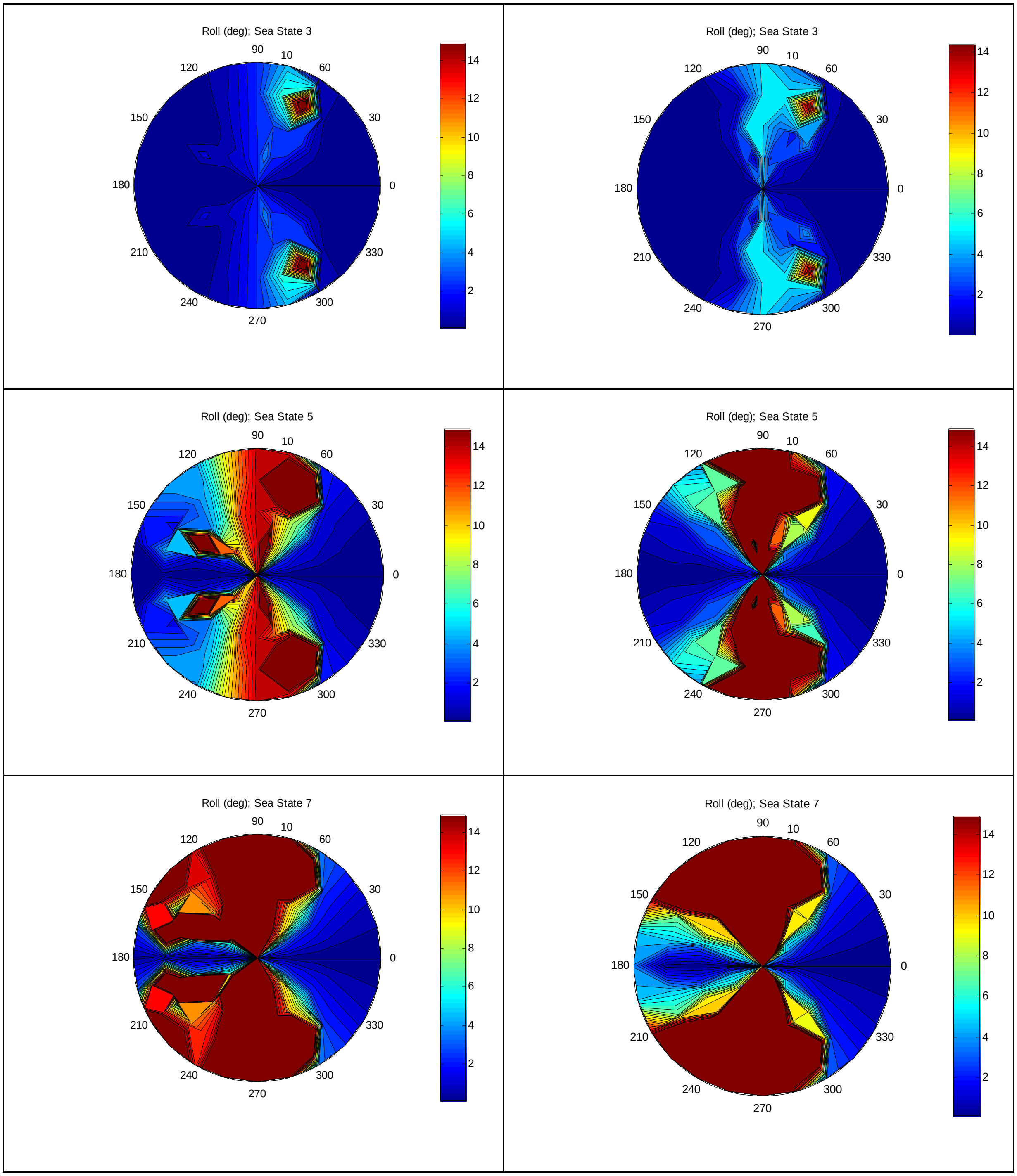
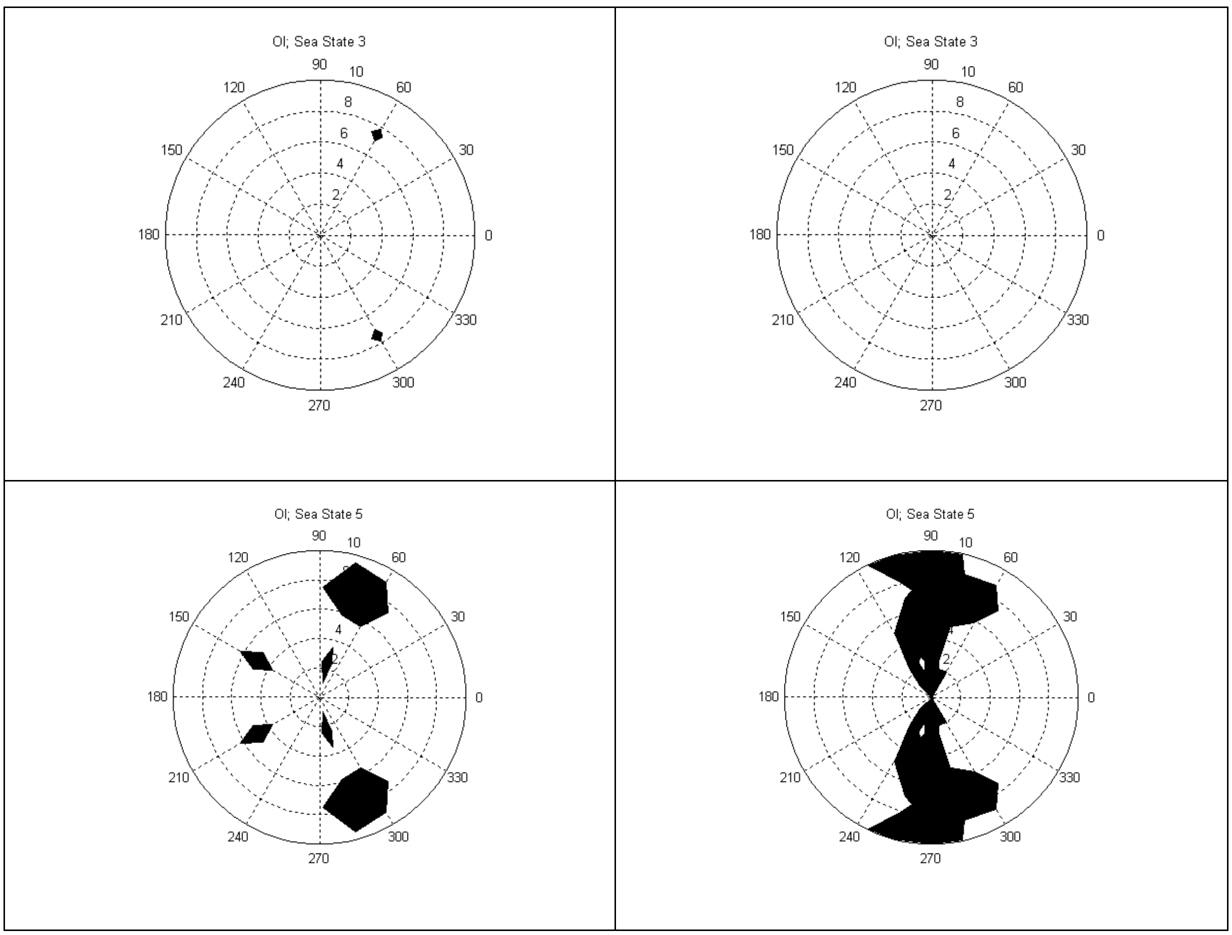


Figure 51. Polar Plot of Roll Motion of the Baseline and Lengthened Variant DDG-51 at Various Sea States

E. OPERABILITY INDEX

Another measure of the seakeeping of the two vessels is the Operability Index polar plot. These graphs allow a visual representation of the actual range of operating conditions (speed, wave direction, and sea state) that the ship can safely operate and conduct its mission, where the white represents when the ship can operate and the black is when the ship cannot conduct operations. The limiting factor for a destroyer with regards to seakeeping is the ability to conduct helicopter operations. Figure 52 shows that the lengthened vessel has larger ranges of conditions where it cannot conduct operations.



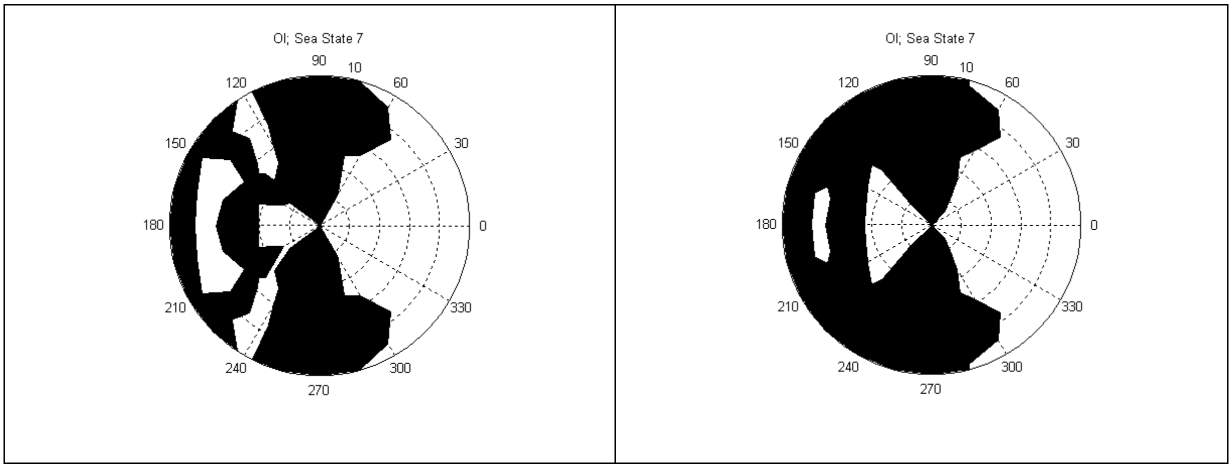


Figure 52. Polar Plot of Operability Index of the Baseline and Lengthened Variant DDG-51 at Various Sea States

F. ADDITIONAL POLAR PLOTS

In Appendices C through F, there are polar plots of several other motions. These motions are not as important as heave, pitch, and roll, but do offer more data on the seakeeping capabilities of the two hullforms.

The polar plots represent a combination of the motions, both translations and rotations, in accelerations. The Slam acceleration is the forward and back acceleration caused by the surge and pitch. The Lateral acceleration the back and forth motion resulting from the sway and yaw. The Vertical acceleration is the up and down motion caused by heave and roll. The Slam motion velocities are also plotted.

G. CHAPTER SUMMARY

The seakeeping analysis provides a graphical representation of the ship motions in heave, pitch, and roll, as well as a series of polar plots that show how these motions affect the operational ability of the two vessels. Though the lengthened DDG-51 variant performed better in the heave and pitch motion, its greater roll motion caused its Operability Index range to decrease.

VII. STRUCTURAL ANALYSIS

A. INTRODUCTION

The structural aspect of ship design is very important, especially for a warship that could encounter some of the worst seas possible. U.S. Navy destroyers historically have had a 30-year service life, but as there have been setbacks in new ship acquisition, the DDG-51 may have to stay in service for 35–40 years. This increase in operational life will test the adequacy of the structural design. The initial hulls from Flight I experienced minor hull cracking at the bow, which resulted in a design change for follow-on hulls and a backfit to the previous ships.

Other than that one issue, the hull of the ARLEIGH BURKE has been a sound design. The structural impact of lengthening the DDG-51 hullform is an important design change due to the increased moments caused by the longer hull. Since cost is such an important issue with new surface ship acquisition, minimizing design changes of this variant is an important design goal. Savings can be realized by minimizing the changes to the hull framing and scantlings of the DDG-51 when designing the lengthened variant.

This research will show a rough order structural analysis of both the DDG-51 Flight IIA and the lengthened variant to compare the structural moments of each. The calculations were performed using Microsoft Excel spreadsheets that can tabulate and plot the necessary forces and distances used to determine the total moments. If the variant's moments do not greatly exceed the baseline destroyer's values and are within Navy structural limits, it will be possible to retain as much of the original structural design as possible and keep the cost of a modified repeat as low as possible.

B. LOADING CONDITIONS

Three different loading conditions will be evaluated that represent the worst operating conditions that the ship will encounter performing its missions. The first of the

conditions is the steady state condition, which will be called still water. This acts like a control, representing the stresses on the hull while balancing the load of the ship against the buoyancy of the hull.

The next two conditions will represent the worst-case scenarios for structural design; the hogging and sagging conditions. Sagging is when the middle of the ship is not properly supported and wants to sag down. Hogging is when the two ends of the ship are not supported. In Figure 53, sagging is represented by the upper ship (1) and hogging is represented by the lower ship (2).

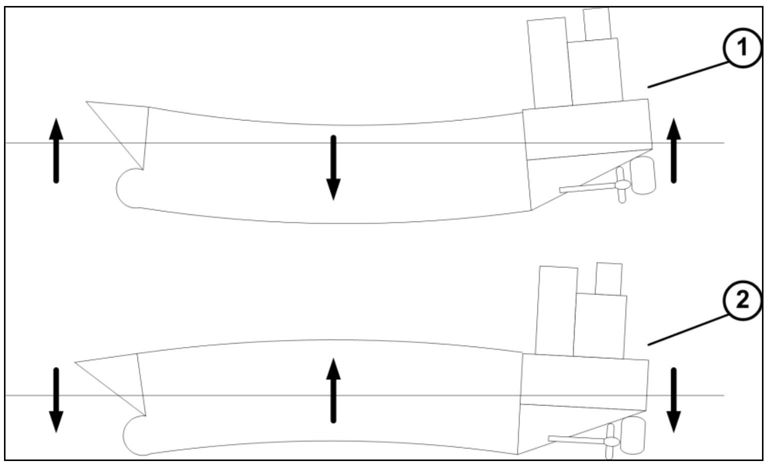


Figure 53. Illustration of Sagging and Hogging Conditions (From Wikipedia Commons, 2010)

Hogging and sagging moments are usually caused by extreme waves. In both cases, the worst case scenario is when the period of the wave is equal to the LWL. The wave height can be determined by checking a sea state chart and finding a height for a period that is near the LWL. Normally in these calculations, a trochoidal waveform is used, but for these calculations, a simpler sinusoidal waveform was utilized.

The DDG-51 hull and the lengthened version have waterline lengths of 142 meters and 160 meters respectively. A NOAA sea state chart shows that waves of that period usually occur in sea state seven, which has waves roughly eight meters in height. These types of conditions are commonly found in the North Atlantic and around the Cape

of Good Hope and Cape Horn, all operating areas of the DDG-51 class destroyer. Figures 54 and 55 show the hogging and sagging waves as they would appear on both the short and long versions of the hull.

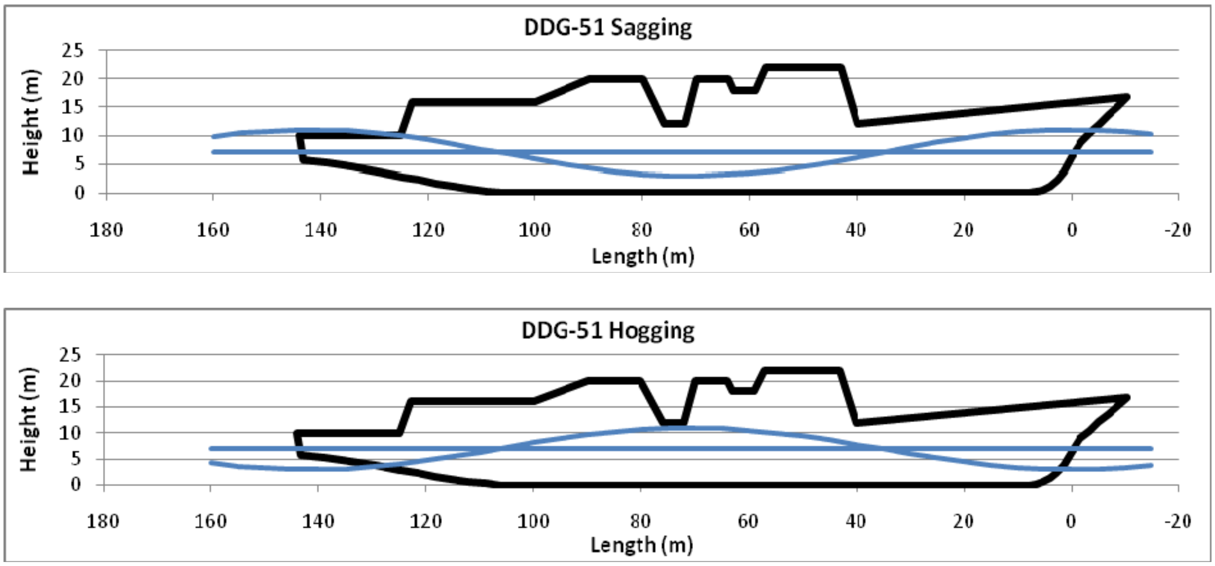


Figure 54. Sagging and Hogging Wave Forms against the DDG-51 Profile

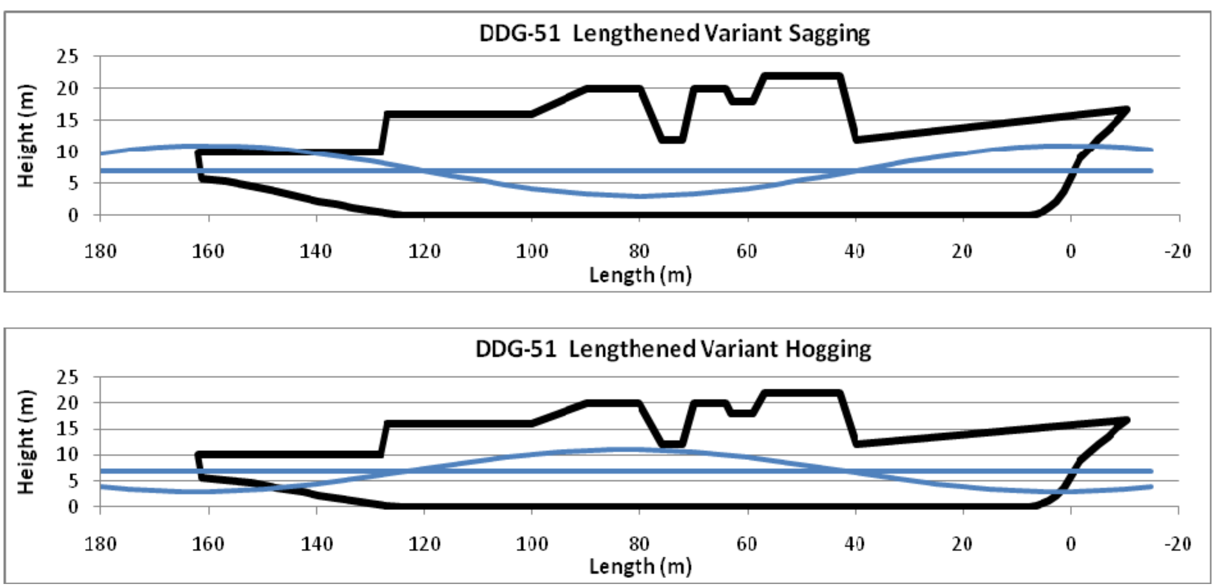


Figure 55. Sagging and Hogging Wave Forms against the Lengthened DDG-51 Profile

In both the short and long versions, the sagging wave is large enough to swamp the stern weather deck of the destroyer, which is not unheard of when operating in sea states this high.

C. PAYLOAD DISTRIBUTION

The next part of the analysis is the payload that is distributed across the ship's length. The standard weight report for a ship would be organized by Ship Work Breakdown Structure (SWBS) group, numbered one through seven. The SWBS groups are broken down into systems and are utilized to determine the weight and stability of the vessel. Unfortunately, for this type of analysis, a consolidated weight table is not useful. The consolidation just sums the weight and gives the Longitudinal Center of Gravity (LCG) of each subgroup, which is grouped around the total LCG for the vessel.

For this study, a distributed weight profile is necessary to show how much weight is at each longitudinal section of the ship. NAVSEA provided an example distributed weight profile for a full load DDG-51 class destroyer, but due to the classification of the actual weights within the distribution; the weights are slightly incorrect. These distributed weight profiles are used to provide the downward forces that would work against the buoyant forces in order to calculate the moments.

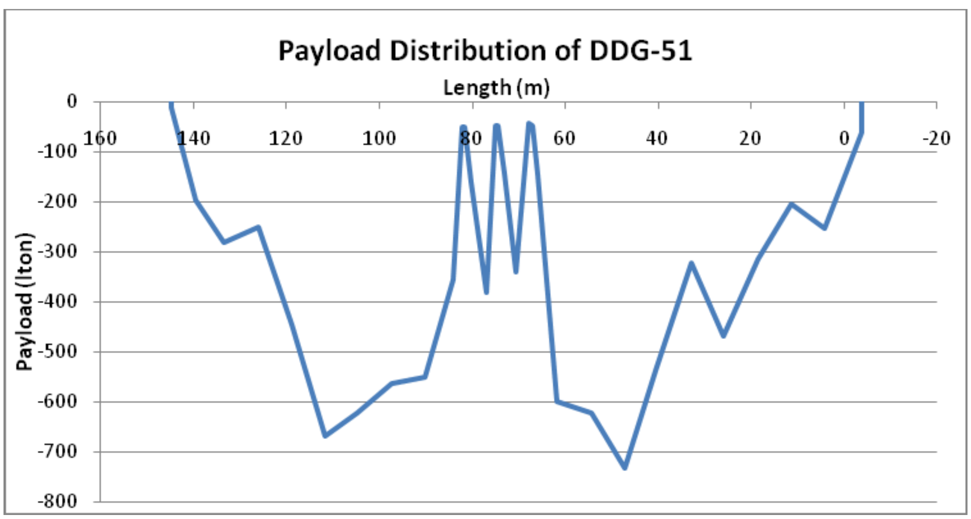


Figure 56. Payload Distribution of the DDG-51

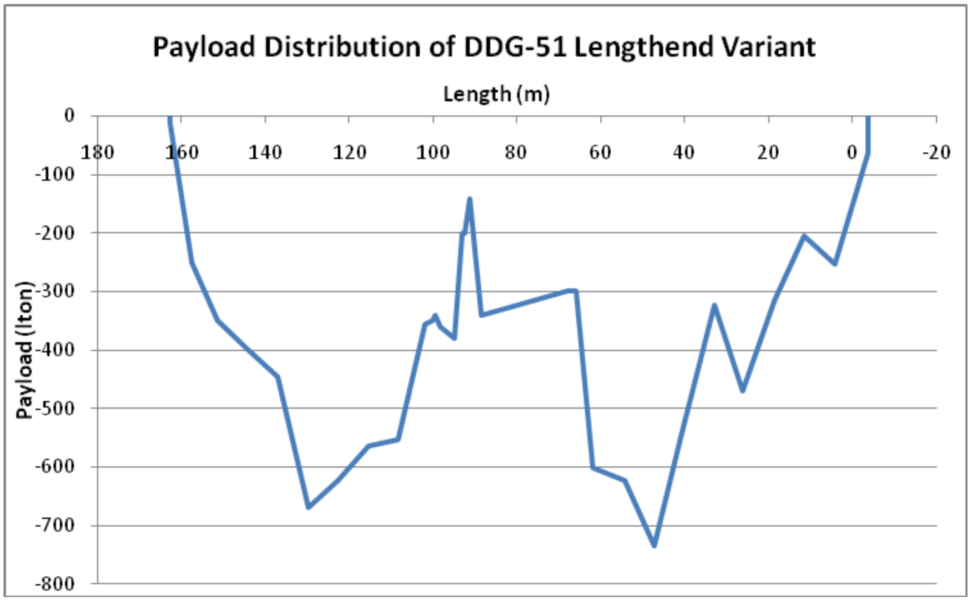


Figure 57. Payload Distribution of the Lengthened DDG-51 Variant

D. BUOYANT FORCE CALCULATIONS

The distributed buoyancy is the next series of calculations performed. Each of the hulls is rendered in Rhinoceros, the same 3-D CAD system used to calculate the hydrostatics from the previous section. Rhino is used to divide the hull into stations approximately 10 meters long each; the first and last stations are slightly longer. Each of these stations is cut from the hull and individually evaluated to determine its displacement. The first displacement is the at the still water condition, a keel draft of seven meters. As mentioned before, this will provide the static, control condition to understand the baseline stress on the hull.

The hogging and sagging section displacements are slightly more difficult to calculate. The height of the wave that represents the hogging and sagging conditions is captured for the midpoint of each section. The hydrostatic calculation of the displacement for the section is performed at a specific draft, which is determined by the wave height at a certain baseline. The center of buoyancy is assumed to act at that midpoint vice calculating the exact LCB for each section. All of these displacements are converted to forces for later calculations.

One difficult part of the process is determining the correct baseline draft from which to base the sagging and hogging condition waves. This is accomplished through a tedious iterative process of performing the hydrostatic calculations at a particular baseline, summing the displacements of each individual station, and ensuring that they will equal the static displacement of the ship. In simpler terms, the sum of the different stations' displacement at its particular draft in hog or sag has to be equal to the total displacement.

The still water, sagging, and hogging conditions for each of the baseline DDG-51 and the DDG-51 lengthened variant are compared in the following series of plots.

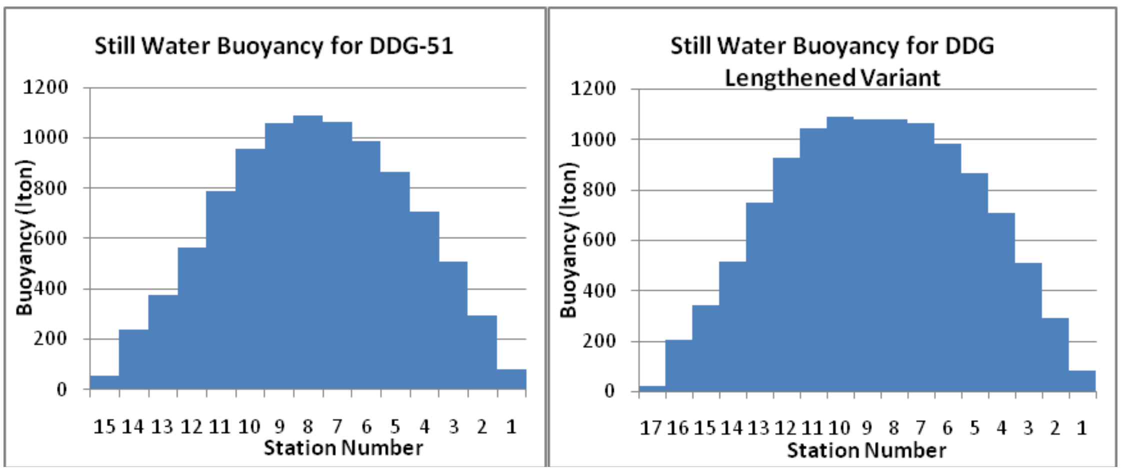


Figure 58. Still Water Buoyancy for Both Destroyers

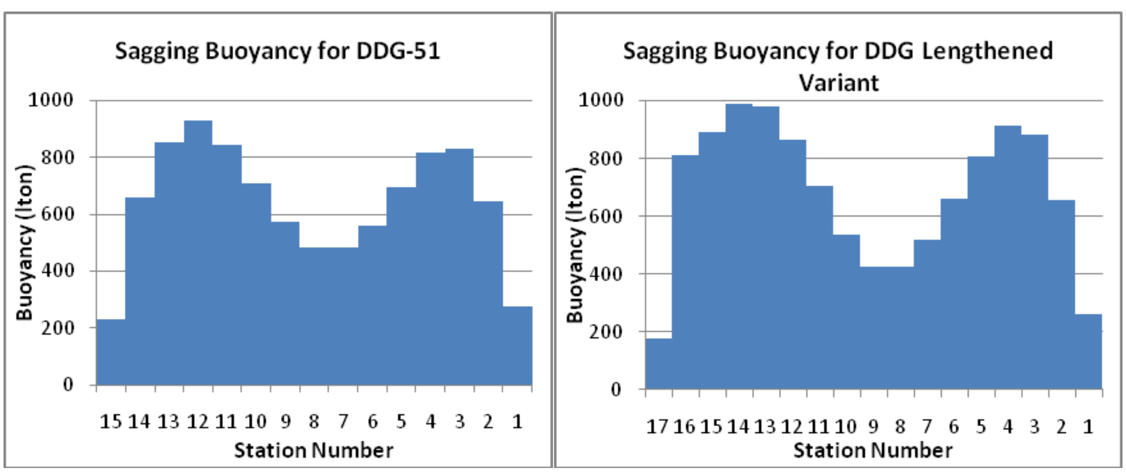


Figure 59. Sagging Buoyancy for Both Destroyers

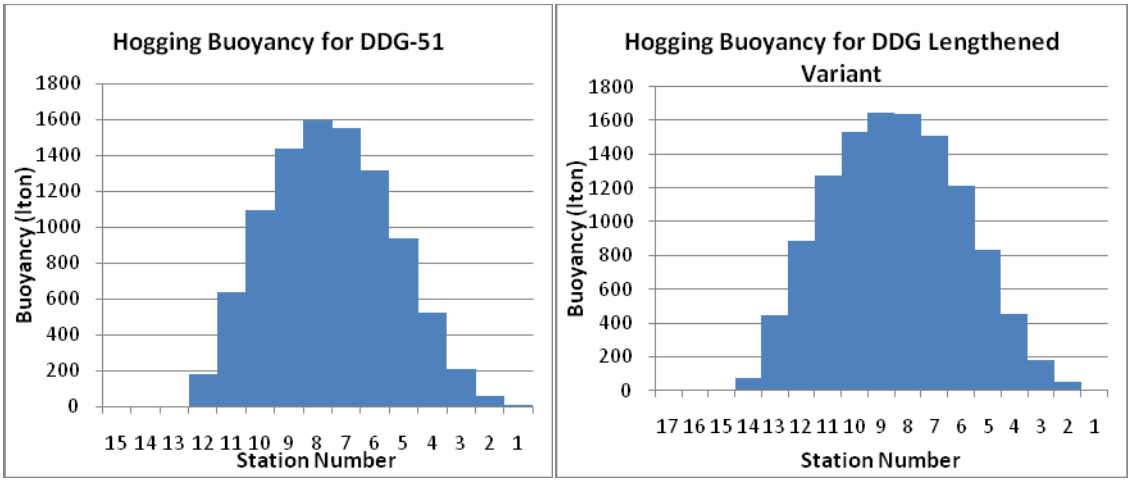


Figure 60. Hogging Buoyancy for Both Destroyers

E. STRUCTURAL ANALYSIS

The next step in this analysis is to convert the buoyancy and payload weights in long tons to the SI unit of force, called Newtons. These forces are then used to calculate the moment by multiplying the force at that station by its distance from amidships. For this analysis the moments caused by buoyancy will all be considered positive and all moments caused by the payload will be considered negative. The entire ship can be considered as one large beam, and solved like a beam bending problem. The standard equation for stress due to a moment is:

$$\sigma = \frac{My}{I} \tag{6}$$

Where M is the moment, y is the distance from the neutral axis, and I is the moment of inertia. Naval architects use a simplified variable representing the moment of inertia and the distance from the neutral axis that describes the two conditions that they are most interested in; the stress at the deck edge (Z_D) and the stress at the keel (Z_K). These are defined by Equations (7) and (8).

$$Z_D = \frac{I}{y_D} \tag{7}$$

$$Z_K = \frac{I}{y_K} \tag{8}$$

The cross section of the ship at the LCB is used to compute the stress values. The cross section is divided into subgroups and the moments of inertia are found and then summed together to find the overall moment of inertia and neutral axis. An example of a combatant cross sectional scantling drawing is shown in Figure 61.

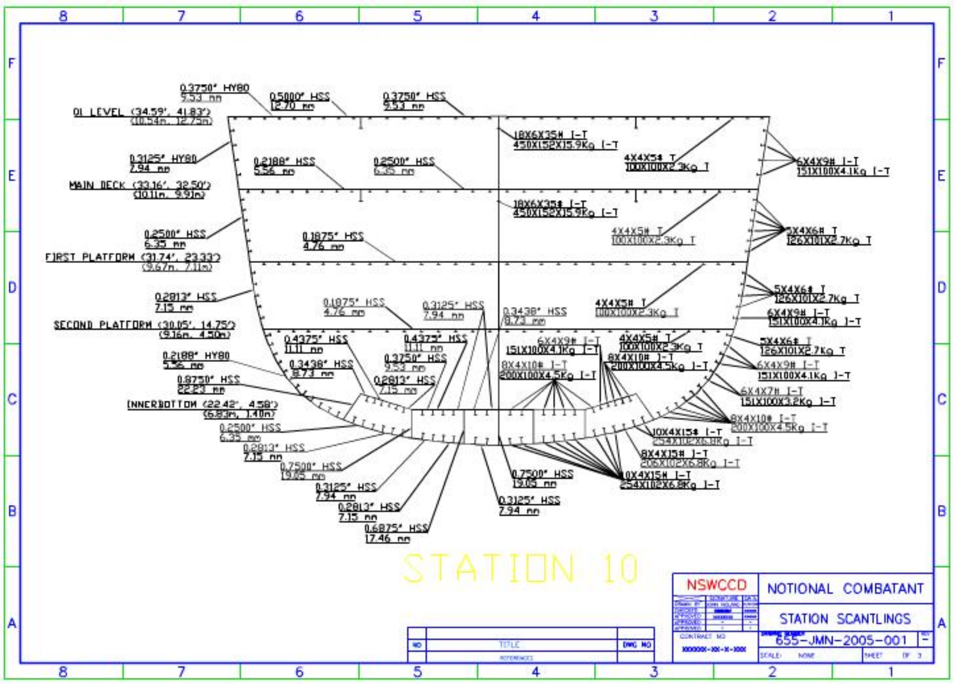


Figure 61. An Example of a Scantling Drawing of a Notional Surface Combatant (From Naval Ship Design, 2009)

Data provided from NAVSEA gave a Z_D value of 4.55m^3 and a Z_K of 5.08 m^3 for the LCB of the destroyer.

Table 14. Stress Values for the Deck and Keel of a Baseline DDG-51

		Still Water	Sagging	Hogging	
Moment	Payload	-284.51	-284.51	-284.51	MN*m
	Buoyancy	246.45	350.99	168.49	MN*m
	Total	-38.06	66.48	-116.02	MN*m
Stress	Deck	8.36	-14.61	25.50	MPa
	Keel	-7.49	13.09	-22.84	MPa

Table 15. Stress Values for the Deck and Keel of a Lengthened DDG-51 Variant

		Still Water	Sagging	Hogging	
Moment	Payload	-428.46	-428.46	-428.46	MN*m
	Buoyancy	341.42	492.02	242.00	MN*m
	Total	-87.04	63.56	-186.46	MN*m
Stress	Deck	19.13	-13.97	40.98	MPa
	Keel	-17.13	12.51	-36.70	MPa

The NAVSEA limits for the keel and deck stresses are 131.27 MPa and 146.72 MPa respectively, in either tension or compression. The baseline DDG-51 Flight IIA stresses shown above are well under those maximum values and the lengthened variant also has stresses well below the limit. In both ships, the worst stresses are experienced in the hogging condition.

Another simple analysis to check is the material strength of the steel that is used in the construction of the DDG-51 destroyer. The deck plating and internal scantlings use High Strength Steel (HSS), which has a yield strength of 690 MPa. Assuming a factor of safety of two, the stress in the hull is greatly below the maximum yield strength of the HSS.

F. CHAPTER SUMMARY

Though this is a rough order of magnitude structural analysis, it shows that by lengthening the hull of a DDG-51 class destroyer by 18 meters and not modifying the structural cross section, the hull still has a large margin before exceeding NAVSEA standards or yielding the metal.

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VIII. CONCLUSION AND RECOMMENDATIONS

A. INTRODUCTION

The U.S. Navy currently has 286 ships and that number continues to decrease. The only solution is to make the current ships last longer and buy new ones, but with recent cost overruns in ship acquisition programs, many programs now have been cut or cancelled. The DDG-1000 was planned to be a 32-ship class, but has been cut to three hulls. The LCS program has floundered for years without a clear path to a viable class of ships. And the cruiser replacement program, CG(X) was canceled in the early months of 2010. These three programs prove that cost is the most critical factor of any ship acquisition program.

The U.S. Navy's next ship needs to reduce costs in every way possible. A solution to this is to reuse a current hullform, a platform that has proved itself in combat situations. This reuse of a hull can save billions of dollars both in design costs and the capital expenditures by the shipyards that will construct the new class. By taking a DDG-51 Flight IIA hull form and inserting a parallel mid-body plug to lengthen it by 18 meters, the Navy can provide the destroyer of the future at a fraction of the cost of the DDG-1000, LCS, and CG(X) programs.

B. ANALYSIS RESULTS

By comparing a variety of other modern surface combatants used by both the United States and our Allies, the average length to beam ratio is 8.53. This is far larger than the current DDG-51 at 7.7. The solution can be to create a modified repeat of this hullform that is lengthened by inserting a section of parallel midbody. For this thesis, the length to beam ratio is increased to 8.6, resulting in a lengthening of 18 meters. This increase in length will be incorporated into the hull using a parallel midbody section and increasing the displacement of the DDG-51 to roughly 11,500 tons.

The lengthened variant of the DDG-51 will have different characteristics than the baseline version. The resistance and propulsion of the ship will change with the increased length and displacement. Instead of requiring more power, as one would expect, the increased L/B ratio reduces the wavemaking resistance on the hull, which results in a 10 MW decrease in power necessary to propel the lengthened variant to 30 knots, the expected operational speed of a destroyer. The less power required to move the longer hullform can drive the use of a more fuel efficient propulsion system than the gas turbines currently installed on DDG-51 Flight IIA destroyers.

Seakeeping is another important attribute that changing the length of a vessel can alter. The three main motions analyzed are heave, pitch, and roll; all motions that are too extreme can limit the operations of the vessel in higher seas. The lengthened variant of the DDG-51 performs better than the baseline destroyer in both the heave and pitch motions, but due to its longer length does not perform as well in the roll motion. This tendency to roll in the higher sea states lowers the lengthened variant's operability index as compared to the baseline DDG-51. Other vessels that have larger L/B ratios conduct flight operations, so a more in-depth analysis to the operational situations when a destroyer would conduct flight operations is necessary to determine if this actually makes the lengthened hullform less capable.

The structural analysis shows that re-utilizing the same ship structures from the DDG-51, the lengthened variant will still comply with the NAVSEA requirements for hogging and sagging moments. Huge costs savings in design and analysis can be realized in the proof that the fundamental hull is strong enough to support the lengthening without major revision to the structure.

C. CONCLUSION

The need for more destroyers is coming; the first of the DDG-51 class vessels has been operational for nearly twenty years. With the future missions of the destroyer including Ballistic Missile Defense, the future fleet must be prepared for the larger missiles and larger sensors that are required to support that mission. The best way to

build a ship now with the margins to handle those future systems and be cost effective is to reuse the DDG-51 Flight IIA hullform and lengthen it.

The data in this thesis has shown that by lengthening the vessel, the volume for mission equipment can greatly increase with an overall reduction in resistance. The lower resistance and propulsion needs can translate into fuel savings over the life of the vessel, totaling millions of dollars. To ensure that the lengthened destroyer will still be able to meet all operational requirements of the current DDG-51, a solution to reduce the roll characteristic will have to be developed. However, this design cost will be small in comparison to a completely new ship design.

D. RECOMMENDATION FOR FURTHER RESEARCH

The U.S. Navy is extremely concerned about the total ownership costs of the current and future fleet. One of the current areas of research is into electric or hybrid drive propulsion systems. Instead of a direct mechanical linkage between the main engine and propeller, electric motors drive the propellers and the power comes from generators. By using an electric drive system, the power needed for ship services and propulsion can be more efficiently applied to diesel engines or gas turbine running at their optimum performance. By running the engines at optimum settings, the wear on the engine is reduced and they operate more efficiently.

Research into designing an all-electric power plant, within this lengthened hullform, that can generate power for the reduced propulsion power requirement and the increasing sensor power need, is viable and valuable research.

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APPENDIX A. RESISTANCE AND PROPULSION DATA FOR THE BASELINE DDG-51

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                University of Michigan
Department of Naval Architecture and Marine Engineering


 Power Prediction Program (PPP-1.8) by M. G. Parsons

 Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate
           Power Prediction Method," International Shipbuilding
            Progress, Vol.29, No.335, July, 1982.
       2. Holtrop,J., "A Statistical Reanalysis of
           Resistance and Propulsion Data," International
           Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: Short Hull - Run6

Input Verification:

     Length of Waterline LWL (m)              =    144.68
     Maximum Beam on LWL (m)                  =     18.50
     Depth at the Bow (m)                     =      0.00

     Mean Draft (m)                           =      7.00
     Draft Forward (m)                        =      6.50
     Draft Aft (m)                            =      7.50

     Block Coefficient on LWL CB              =    0.5070
     Prismatic Coefficient on LWL CP          =    0.6123
     Midship Coefficient to LWL CM=CX         =    0.8280
     Waterplane Coefficient on LWL CWP        =    0.7910

     Center of Buoyancy LCB (% LWL; + Fwd)    =   -1.0000
     Center of Buoyancy LCB (m from FP)       =     73.79
     Molded Volume (m^3)                      =    9499.2
     Deck House/Cargo Frontal Area (m^2)      =    420.00

     Water Type                               =  Salt@15C
     Water Density (kg/m^3)                   =   1025.87
     Kinematic Viscosity (m^2/s)              =   0.118831E-05

     Appen. Drag (% Bare Hull Resistance)     =     10.00

     Bulb Section Area at Station 0 (m^2)     =      0.00
     Vertical Center of Bulb Area (m)         =      0.00

     Transom Immersed Area (m^2)              =     12.00
     Stern Type                               = Normally Shaped
     Design Margin on RT,PE,REQ.THR (%)       =     10.00
     Propulsion Type                          = Twin Screw

     Propeller Diameter (m)                   =      5.18
     Propeller Pitch Diameter Ratio P/Dp      =    1.0000

     Wetted Surface (m^2)                     =   3032.00
     Half Angle of Entrance (deg)             =     10.90
```

University of Michigan
Department of Naval Architecture and Marine Engineering

Power Prediction Program (PPP-1.8) by M. G. Parsons

Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate Power Prediction Method," International Shipbuilding Progress, Vol.29, No.335, July, 1982.
2. Holtrop,J., "A Statistical Reanalysis of Resistance and Propulsion Data," International Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: Short Hull - Run6

Speed, Resistance Coefficients and Frictional Resistance RF(N):

V(kts)	V(m/s)	FN	SLRATIO	CF	CR	CA	RF
4.00	2.06	0.0546	0.1836	0.001832	0.000945	0.000439	12062.4
8.00	4.12	0.1093	0.3672	0.001671	0.000800	0.000439	44011.4
12.00	6.17	0.1639	0.5508	0.001586	0.000726	0.000439	94018.6
16.00	8.23	0.2185	0.7344	0.001530	0.000863	0.000439	161231.7
20.00	10.29	0.2731	0.9180	0.001489	0.001285	0.000439	245092.2
24.00	12.35	0.3278	1.1016	0.001456	0.001533	0.000439	345188.1
28.00	14.40	0.3824	1.2852	0.001429	0.002566	0.000439	461195.3
32.00	16.46	0.4370	1.4688	0.001407	0.004093	0.000439	592847.4

Remaining Resistance Components (N):

V(kts)	Form RF*K1	Appendage RAPP	Wave RW	Bulb RB	Transom RTR	Correlation RA	Air Drag RAIR
4.00	1814.7	1828.5	0.0	0.0	4407.8	2889.1	749.7
8.00	6621.2	6509.3	48.7	0.0	14411.4	11556.5	2998.9
12.00	14144.3	13704.0	3696.1	0.0	25181.4	26002.1	6747.6
16.00	24256.0	25211.8	34742.4	0.0	31888.1	46225.9	11995.7
20.00	36872.1	45661.6	144949.8	0.0	29702.0	72228.0	18743.3
24.00	51930.8	70873.6	297823.2	0.0	13793.5	104008.3	26990.4
28.00	69383.1	128924.0	758661.4	0.0	0.0	141566.8	36736.9
32.00	89189.1	231771.5	1635678.5	0.0	0.0	184903.6	47982.9

Resistance, Effective Power, Propulsion Factors and Required Thrust

V(kts)	RT(N)	PE(kW)	w	t	REQ.THR(N)	etaH	etaRR
4.00	26127.5	53.76	0.0651	0.0790	28367.7	0.9852	0.9809
8.00	94773.0	390.04	0.0642	0.0790	102899.1	0.9842	0.9809
12.00	201843.4	1246.04	0.0637	0.0790	219150.0	0.9837	0.9809
16.00	369106.7	3038.13	0.0634	0.0790	400754.8	0.9833	0.9809
20.00	652573.9	6714.20	0.0631	0.0790	708527.2	0.9831	0.9809
24.00	1001668.6	12367.16	0.0629	0.0790	1087554.1	0.9829	0.9809
28.00	1756114.3	25295.63	0.0628	0.0790	1906687.8	0.9827	0.9809
32.00	3060610.3	50384.01	0.0627	0.0790	3323034.5	0.9826	0.9809

Design Margin Has Been Included in RT, PE, and REQ.THR = RT/(1-t).

APPENDIX B. RESISTANCE AND PROPULSION DATA FOR THE LENGTHENED DDG-51 VARIANT

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              University of Michigan
Department of Naval Architecture and Marine Engineering


 Power Prediction Program (PPP-1.8) by M. G. Parsons

 Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate
           Power Prediction Method," International Shipbuilding
            Progress, Vol.29, No.335, July, 1982.
       2. Holtrop,J., "A Statistical Reanalysis of
           Resistance and Propulsion Data," International
           Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: DDG Try

Input Verification:

     Length of Waterline LWL (m)                =    162.68
     Maximum Beam on LWL (m)                    =     18.50
     Depth at the Bow (m)                       =      0.00

     Mean Draft (m)                             =      7.00
     Draft Forward (m)                          =      6.50
     Draft Aft (m)                              =      7.50

     Block Coefficient on LWL CB                =    0.5415
     Prismatic Coefficient on LWL CP            =    0.6544
     Midship Coefficient to LWL CM=CX           =    0.8275
     Waterplane Coefficient on LWL CWP          =    0.8144

     Center of Buoyancy LCB (% LWL; + Fwd)      =   -1.0000
     Center of Buoyancy LCB (m from FP)         =     82.97
     Molded Volume (m^3)                        =   11407.8
     Deck House/Cargo Frontal Area (m^2)        =    420.00

     Water Type                                 =  Salt@15C
     Water Density (kg/m^3)                     =   1025.87
     Kinematic Viscosity (m^2/s)                =   0.118831E-05

     Appen. Drag (% Bare Hull Resistance)       =     10.00

     Bulb Section Area at Station 0 (m^2)       =      0.00
     Vertical Center of Bulb Area (m)           =      0.00

     Transom Immersed Area (m^2)                =     12.00
     Stern Type                                 = Normally Shaped
     Design Margin on RT,PE,REQ.THR (%)         =     10.00
     Propulsion Type                            = Twin Screw

     Propeller Diameter (m)                     =      5.18
     Propeller Pitch Diameter Ratio P/Dp        =    1.7200

     Wetted Surface (m^2)                       =   3032.00
     Half Angle of Entrance (deg)               =     11.74
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University of Michigan
Department of Naval Architecture and Marine Engineering

Power Prediction Program (PPP-1.8) by M. G. Parsons

Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate Power Prediction Method," International Shipbuilding Progress, Vol.29, No.335, July, 1982.
2. Holtrop,J., "A Statistical Reanalysis of Resistance and Propulsion Data," International Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: DDG Try

Speed, Resistance Coefficients and Frictional Resistance RF(N):

V(kts)	V(m/s)	FN	SLRATIO	CF	CR	CA	RF
4.00	2.06	0.0515	0.1731	0.001803	0.000926	0.000411	11872.7
8.00	4.12	0.1030	0.3463	0.001646	0.000783	0.000411	43349.9
12.00	6.17	0.1546	0.5194	0.001563	0.000715	0.000411	92641.2
16.00	8.23	0.2061	0.6926	0.001508	0.000852	0.000411	158911.4
20.00	10.29	0.2576	0.8657	0.001468	0.001223	0.000411	241612.7
24.00	12.35	0.3091	1.0388	0.001436	0.001546	0.000411	340341.1
28.00	14.40	0.3606	1.2120	0.001409	0.001952	0.000411	454778.6
32.00	16.46	0.4122	1.3851	0.001387	0.003457	0.000411	584663.8

Remaining Resistance Components (N):

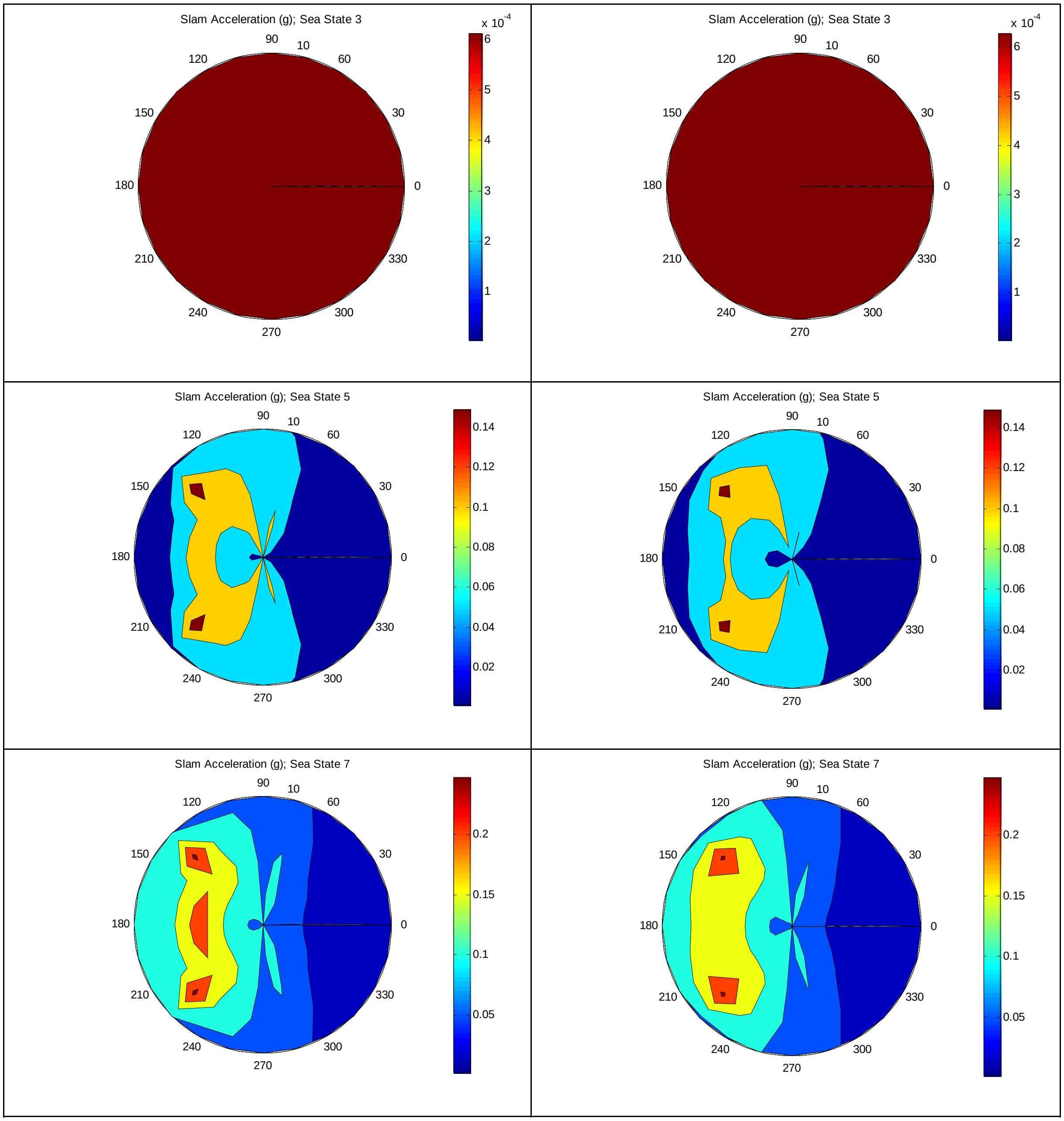
	Form	Appendage	Wave	Bulb	Transom	Correlation	Air Drag
V(kts)	RF*K1	RAPP	RW	RB	RTR	RA	RAIR
4.00	1698.4	1797.4	0.0	0.0	4402.5	2704.4	749.7
8.00	6201.2	6398.3	62.4	0.0	14369.5	10817.5	2998.9
12.00	13252.3	13500.8	4074.7	0.0	25039.8	24339.4	6747.6
16.00	22732.2	24873.1	35534.7	0.0	31552.6	43270.1	11995.7
20.00	34562.7	44289.8	137675.6	0.0	29046.8	67609.5	18743.3
24.00	48685.7	70678.0	305092.1	0.0	12661.4	97357.7	26990.4
28.00	65056.0	108477.7	564942.3	0.0	0.0	132514.6	36736.9
32.00	83636.1	204158.0	1373279.8	0.0	0.0	173080.3	47982.9

Resistance, Effective Power, Propulsion Factors and Required Thrust

V(kts)	RT(N)	PE(kW)	w	t	REQ.THR(N)	etaH	etaRR
4.00	25547.6	52.57	0.0763	0.0902	28080.0	0.9850	0.9400
8.00	92617.5	381.17	0.0753	0.0902	101798.0	0.9839	0.9400
12.00	197555.5	1219.57	0.0748	0.0902	217137.8	0.9834	0.9400
16.00	361756.8	2977.64	0.0745	0.0902	397615.3	0.9830	0.9400
20.00	630894.4	6491.15	0.0742	0.0902	693430.6	0.9827	0.9400
24.00	991987.1	12247.63	0.0740	0.0902	1090315.9	0.9825	0.9400
28.00	1498756.6	21588.57	0.0738	0.0902	1647317.9	0.9824	0.9400
32.00	2713480.8	44669.54	0.0737	0.0902	2982449.3	0.9822	0.9400

Design Margin Has Been Included in RT, PE, and REQ.THR = RT/(1-t).

APPENDIX C. POLAR PLOTS OF SLAM ACCELERATION OF BOTH VESSELS IN VARIOUS SEA STATES



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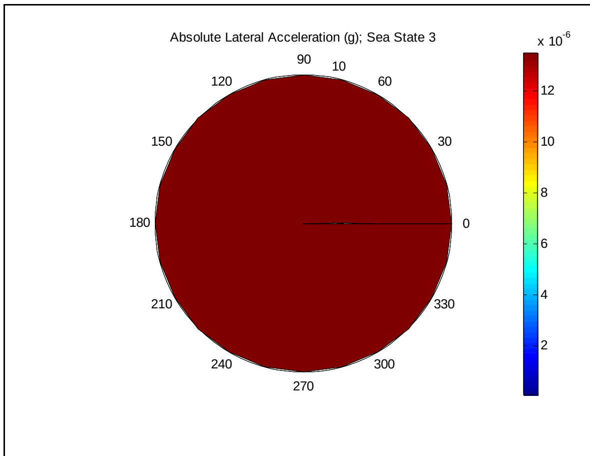
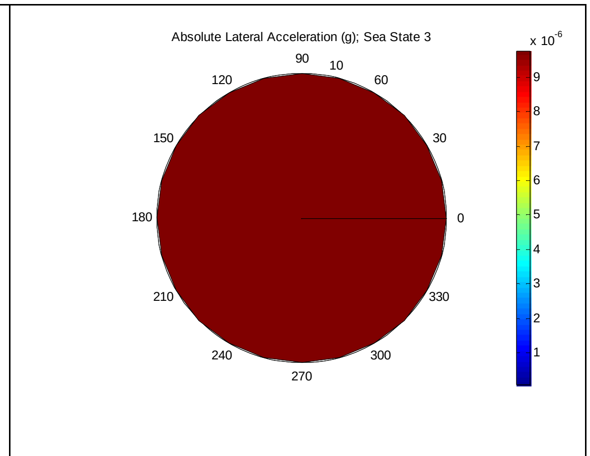
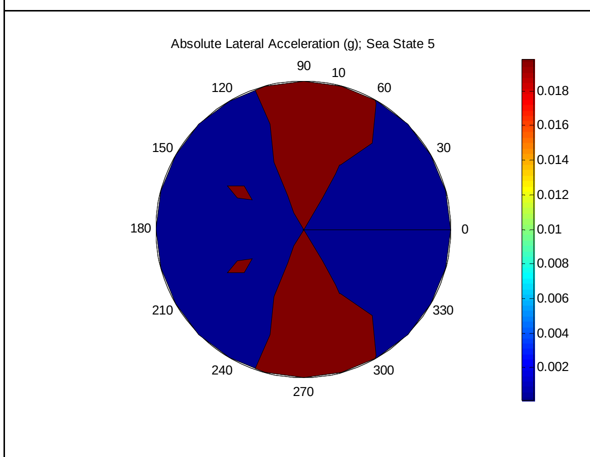
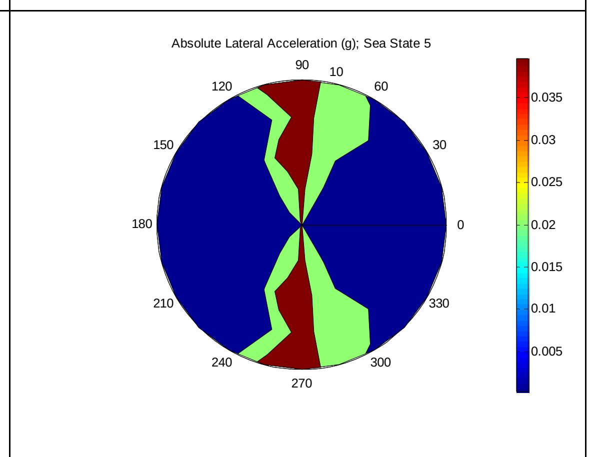
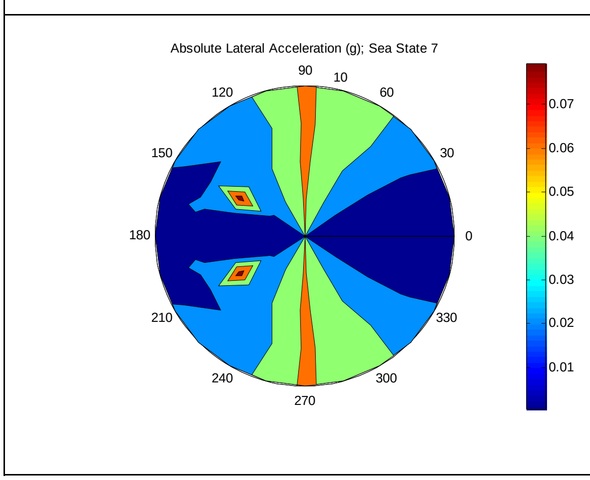
APPENDIX D. POLAR PLOTS OF LATERAL ACCELERATION OF BOTH VESSELS IN VARIOUS SEA STATES

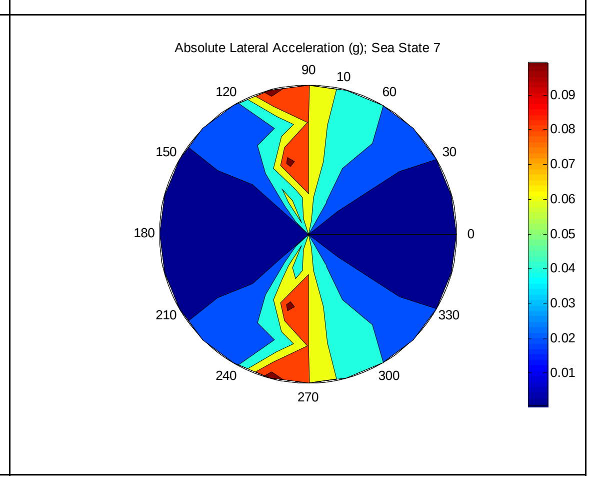












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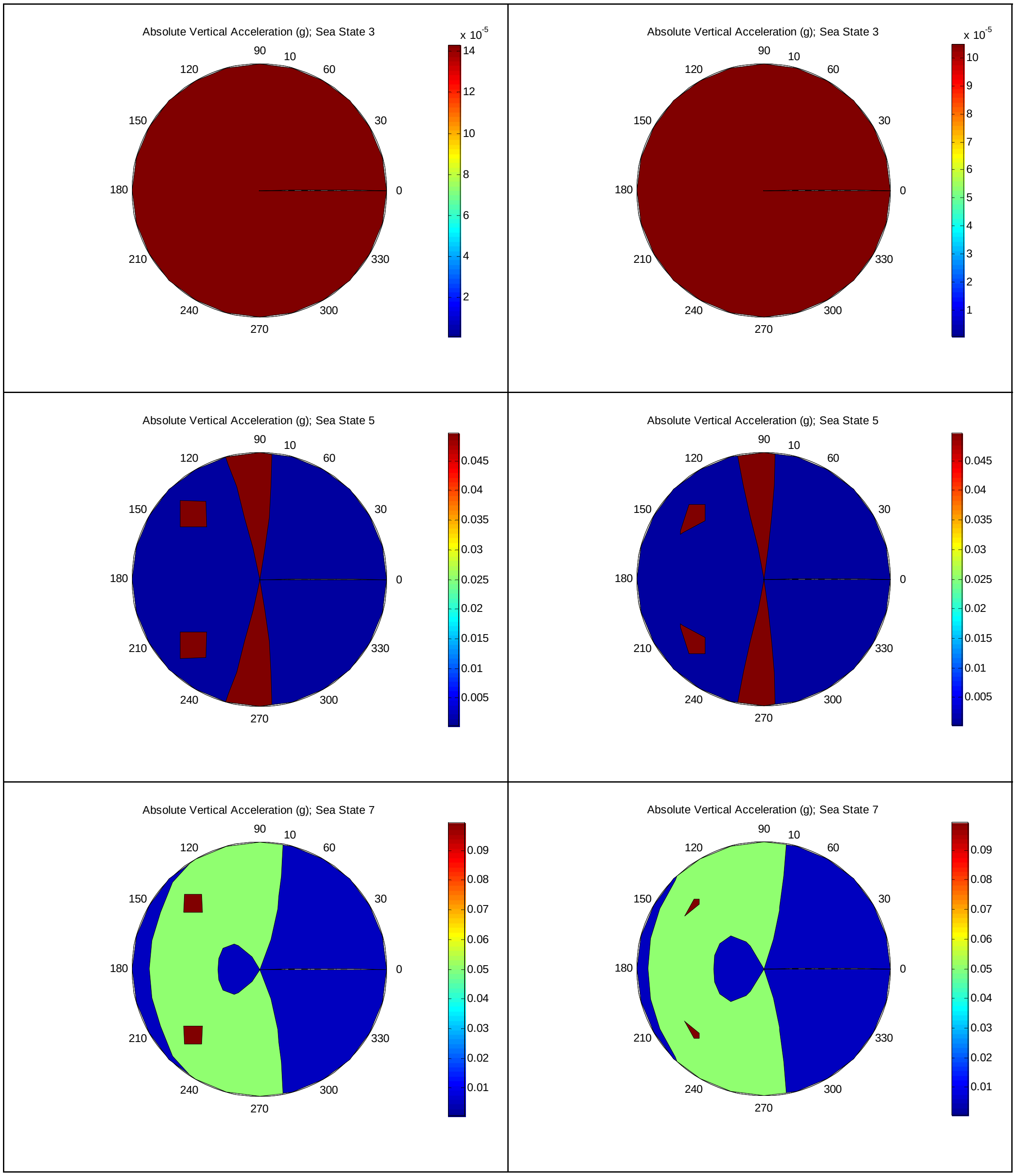
APPENDIX E. POLAR PLOTS OF VERTICAL ACCELERATION OF BOTH VESSELS IN VARIOUS SEA STATES



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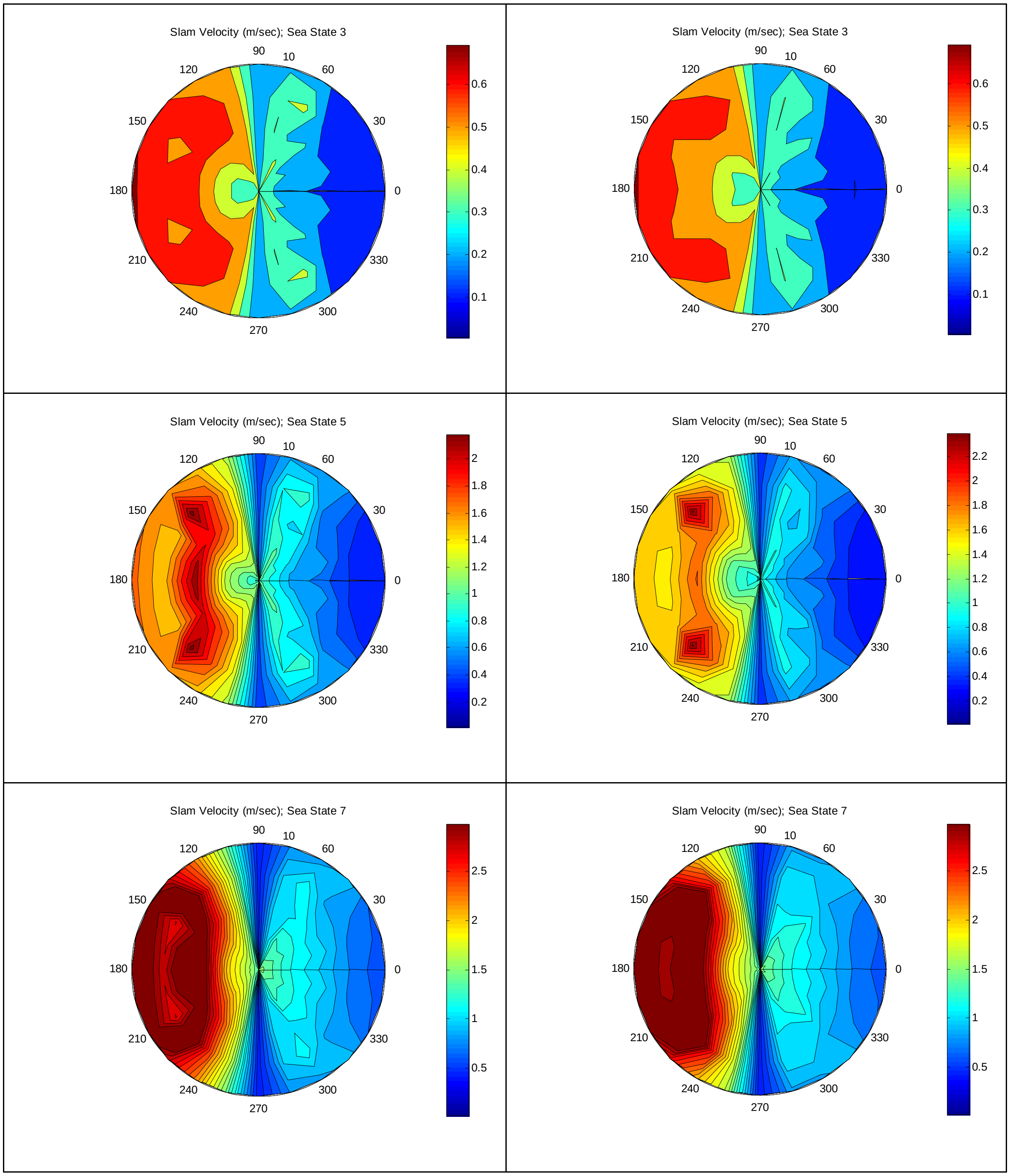
APPENDIX F. POLAR PLOTS OF SLAM VELOCITY OF BOTH VESSELS IN VARIOUS SEA STATES



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